Investigating visual short-term memory capacity within and between hemifields

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. This copy has been supplied on the understanding that it is copyright material and that no quotation from the thesis may be published without proper acknowledgement.

Experiments 1, 2 & 3 of the thesis (shown in Part One) have been included in a jointly authored publication as follows:

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Jessica Holt designed the experiments, collected the data and carried out all data analysis for these chapters with the supervision of Dr Jean-Francois Delvenne. The manuscripts were written by Jessica Holt with guidance on drafts from Dr Jean-Francois Delvenne.

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To my family I dedicate this thesis.

Abstract

A number of non-mnemonic tasks have revealed the existence of a bilateral field advantage (BFA; i.e. the increase in processing capacity when information is distributed across the two visual fields relative to within a single hemifield) in visual processing. Recent research suggests that the BFA may also extend to visual short-term memory (VSTM). However to date, studies have produced inconsistent findings, demonstrating a BFA in VSTM for spatial locations and orientations but not for colours (Delvenne, 2005; Umemoto, Drew, Ester, & Awh, 2010). Two possible hypotheses may account for those findings. The first suggests that the BFA is a feature of processing spatial information but not identity information (the stimulus domain hypothesis) whilst the second claims that the BFA is a feature of attentional selective processing (the attentional selection hypothesis). With the primary aim to uncover the conditions which promote a BFA in VSTM, the present thesis tested those hypotheses. Since the stimulus domain hypothesis predicts no possibility of a BFA for colour VSTM, Part One investigated whether colour VSTM may exhibit a BFA when the task demands on selective attention are increased. The findings revealed this to be the case, highlighting that the requirement to attentionally filter spatially distinct target stimuli from distracter stimuli promoted the BFA. In Part Two, selective attention was also found to promote a BFA in colour VSTM during maintenance. Specifically, the findings suggest that bilaterally encoded items can better survive decay in VSTM when spatial selective attention is oriented to stimuli locations at the encoding stage. Overall, the findings strongly suggest that the BFA in VSTM is a signature of attentional selective processing during VSTM encoding and VSTM maintenance. Those findings have important implications for our understanding of the capacity limits of VSTM and attention, and interhemispheric communication more generally.

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Abbreviations

BFA	Bilateral field advantage
BOLD	Blood oxygen level-dependent
CDA	Contralateral delay activity
EOG	Electrooculography
fMRI	Functional magnetic resonance imaging
MOT	Multiple object tracking
VSTM	Visual short-term memory

Preface

Every day, humans process a vast amount of visual information. The ability to do so is critical to many everyday tasks whether it's driving a car, locating items in the supermarket or simply walking down the street. In many cases, we need to remember the visual information that we have seen when it is no longer in view. Imagine crossing a road with two-way traffic. An individual must continuously maintain a representation of the cars on the left whilst looking right, and vice versa, to make a judgement of when it is safe to cross.

Visual short-term memory (VSTM) is the cognitive system that allows humans to temporarily retain relevant visual information. As a crucial component of human functioning, many studies have explored the amount and nature of information that can be stored (Luck & Vogel, 1997). The present thesis delves deeper into our understanding of this system. Specifically, the following experiments reported here address the extent to which VSTM is influenced by the spatial distribution of items across the visual field.

The present thesis explores an effect called the bilateral field advantage (BFA). The BFA reveals that visual information can be processed more efficiently when it is distributed between the two visual fields relative to when all of the information is presented in a single visual hemifield. At present, studies have revealed inconsistent evidence of the BFA in VSTM (e.g. Delvenne, 2005), and thus the present thesis aims to explore when and why this effect is observed.

It is widely acknowledged that the capacity of VSTM is extremely limited with the ability to store only 3-4 objects simultaneously (Luck & Vogel, 1997). Therefore, understanding how we can best utilise this limited capacity system is highly important. Exploring how the spatial distribution of objects within and across hemifields can influence VSTM storage is one way that we can further this

understanding. In addition, this factor is likely to generate a number of practical applications, having important consequences for the way VSTM is assessed in future experimental work. Furthermore, it may influence the design characteristics of important visual interfaces that humans must interact with every day, and help realise the potential to minimise human error in a variety of information-rich situations, such as road- and air-traffic accidents.

In the first section of this thesis, a review of the existing literature on the BFA in VSTM is presented which provides direction to the experimental work undertaken. Subsequently, eight studies explore the nature of the BFA in VSTM tasks and uncover the conditions in which the BFA is observed. The findings and their implications are discussed in the closing chapter.

1 Literature Review

1.1 The bilateral field advantage in visual processing

Previous research suggests that the efficiency of visual processing is constrained by the spatial distribution of information across a visual scene. For instance, studies have shown that factors such as inter-object distance (e.g. Toet & Levi, 2002) and the position of objects in the periphery (or eccentricity, e.g. Carrasco, Evert, Chang, & Katz, 1995) can reduce visual acuity, influencing the ability to effectively discriminate visual information. The visual scene can also be spatially divided from the point of central fixation forming two visual hemifields delineated by the vertical midline. Subsequently, studies have investigated whether the spatial distribution of items within and across the visual hemifields can also influence visual processing capacity (e.g. Alvarez & Cavanagh, 2005).

In order to investigate how the spatial distribution of information within and across hemifields influences visual processing, studies have assessed visual processing capacity whilst participants maintain a central fixation in order to ensure that stimuli are presented to the correct portion of the visual field (for a review of divided field methodologies, see Bourne, 2006). One established effect of divided field presentation that has been frequently observed in the literature is the bilateral field advantage (BFA). The BFA reveals that visual processing capacity can be increased when to-be-processed information is divided between the two visual fields relative to when the same information is presented within a single hemifield. Studies have shown that the BFA can increase both the speed of processing (e.g. Awh & Pashler, 2000) and the number of visual stimuli that can be simultaneously processed (e.g. Delvenne, Castronovo, Demeyere, & Humphreys, 2011a).

The BFA was first demonstrated by Dimond and Beaumont (1971). They showed that the ability to report pairs of briefly presented digits (250ms) displayed across hemifields (one digit per hemifield) was better relative to when both digits were presented within a single hemifield. Since then, the BFA has been observed in a number of tasks requiring different types of visual processing such as visual enumeration (Delvenne et al., 2011a), multiple object tracking (Alvarez & Cavanagh, 2005; Hudson, Howe, & Little, 2012) visual search (Alvarez, Gill, & Cavanagh, 2012; Shipp, 2011), the discrimination and detection of visual stimuli (Chakravarthi & Cavanagh, 2009; Reardon, Kelly, & Matthews, 2009; Yoshizaki, Weissman, & Banich, 2007) and the rapid identification of letters (Scalf, Banich, Kramer, Narechania, & Simon, 2007) and digits (Awh & Pashler, 2000). In addition, the BFA has been observed in perceptual matching tasks across numerous stimulus domains such as faces (Compton, 2002; Compton, Feigenson, & Widick, 2005), letters (Banich & Belger, 1990; Belger & Banich, 1992, 1998; Cherbuin & Brinkman, 2005; Larson & Brown, 1997; Ludwig, Jeeves, Norman, & DeWitt, 1993; Weissman & Banich, 2000), geometric shapes (Collin, Mcmullen, & Seguin, 2009; Maertens & Pollman, 2005) and patterns (Jeeves & Lamb, 1988; Larson & Brown, 1997; Norman, Jeeves, Milne, & Ludwig,1992). Furthermore, a number of studies have highlighted that visual processing speed can be improved when identical copies of a stimulus are simultaneously displayed in the left and right hemifields relative to within hemifield single stimulus presentations (Baird & Burton, 2008; Hatta, Kawakami, Kogure, & Itoh, 2002; Ratinkx & Fias, 2007), an effect known as bilateral redundancy gain.

Drawing upon the neuroanatomical organisation of the visual system, in which information within each hemifield is initially projected to the contralateral hemisphere of the brain (Eviatar & Zaidel, 1994; Gazzaniga, 2000), the current view is that the BFA is a direct effect of engaging both cerebral hemispheres when to-be-processed information is divided across hemifields (Alvarez & Cavanagh, 2005;

Banich, 1998). A fundamental question is whether foveal representations are also divided at the midline between the two hemispheres (Ellis & Brysbaert, 2010; Lavidor & Walsh, 2004). Whilst this is a subject of debate, evidence supporting this possibility suggests that items presented as close as 0.5 degrees from fixation may be exclusively projected to the contralateral hemisphere (for a discussion, see Lavidor & Walsh, 2004).

With the projection of visual information to separate hemispheres, research suggests that the cerebral hemispheres have the capacity to function independently and in parallel (e.g. Alvarez & Cavanagh, 2005; Holtzman & Gazzaniga, 1985; Luck, Hillyard, Mangun, & Gazzaniga, 1989, 1994). Supporting this possibility, a number of studies have shown that split-brain patients, whom exhibit a disconnection between the cerebral hemispheres due to damage to the corpus callosum, can still concurrently process lateralised visual information presented to the left and right hemifields (e.g. Holtzman & Gazzaniga, 1985; Luck et al., 1994). Furthermore, those studies also suggest that the maintenance of hemispheric independence can improve overall processing capacity, revealing that split-brain patients can encode more visual information (Holtzman & Gazzaniga, 1985) and detect visual information more quickly (Luck et al., 1994) in bilateral visual displays relative to healthy controls.

The BFA as a signature of independent parallel processing of the cerebral hemispheres has indeed been suggested in the literature (e.g. Alvarez & Cavanagh, 2005; Delvenne, 2005; Kraft et al., 2005; Luck et al., 1989, 1994; Sereno & Kosslyn, 1991). The study by Luck and colleagues (1994) also revealed that a BFA emerged when split-brain patients were required to visually search for targets in an array of distracters. They showed that visual search times were almost twice as fast when the information was divided across hemifields. Alvarez and Cavanagh (2005) have since discovered similar findings in healthy participants, revealing that participants were able to attentionally track twice as many moving

stimuli in a multiple object tracking task (MOT; see Pylyshyn & Storm, 1988) when the stimuli were presented across hemifields relative to within hemifields. Specifically, they showed that four stimuli divided equally across hemifields could be tracked at no extra cost relative to only two stimuli within a single hemifield (see Figure 1.1). Therefore, the findings indicate the possibility of independent hemispheric resources that can function in parallel.

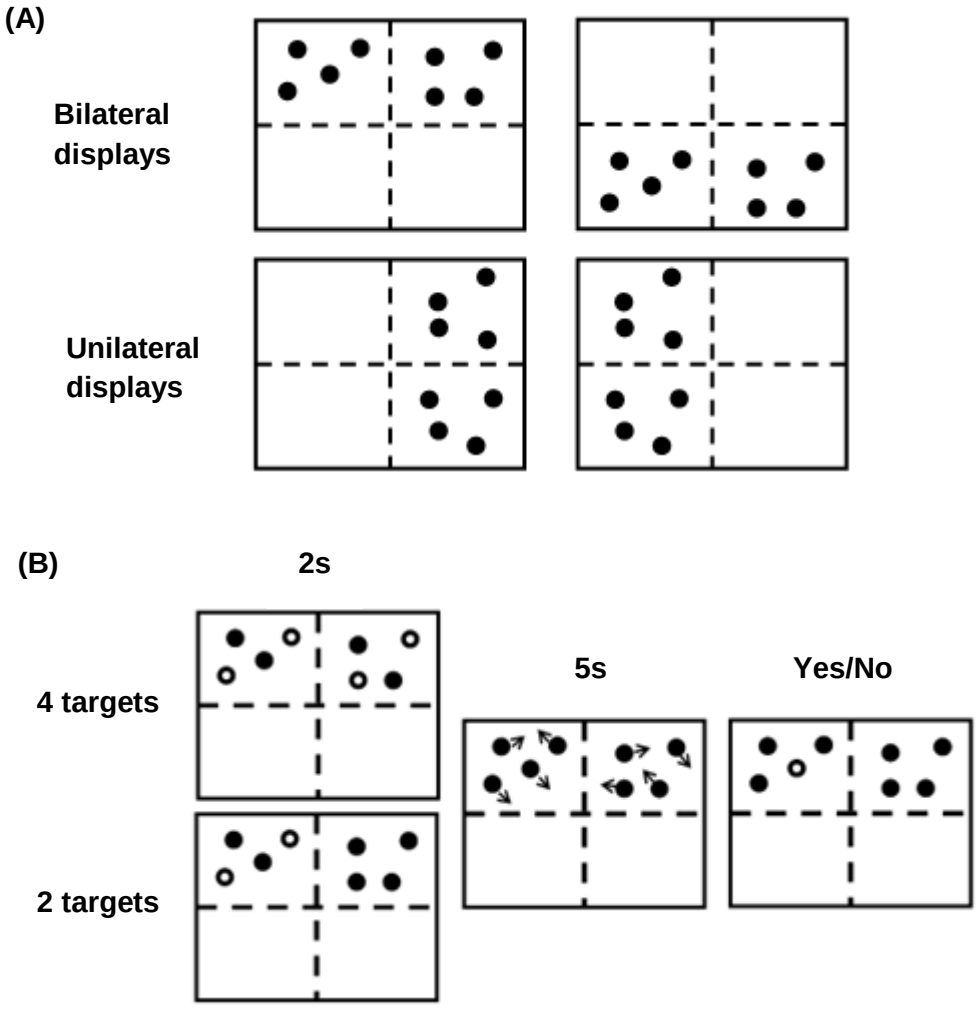

Figure 1.1: An illustration of the displays (A) and trial procedure (B) adapted from Alvarez and Cavanagh's (2005) Experiment 3. Participants were required to track two or four moving targets that were indicated at the beginning of each trial (white circles). At the end of the trial, participants made a yes or no response to indicate whether the probe (white circle) was one of the original targets. Performance in the two and four target conditions above was equivalent, revealing that twice as many stimuli can be tracked when the stimuli are presented bilaterally.

However, numerous demonstrations of the BFA have also occurred in tasks which require the integration of information across hemispheres. For instance, the BFA has been observed across a number of perceptual matching tasks which demand the comparison of information displayed in opposite hemifields (e.g. Banich & Belger, 1990). Indeed, Eviatar and Zaidel (1994) demonstrated that split-brain patients are unable to perform those match judgements, highlighting the importance of callosal transfer in the task. Therefore, Banich and colleagues (e.g. Banich & Belger, 1990; Belger & Banich, 1992, 1998; Weissman & Banich, 2000) suggest that the BFA may also be influenced by the interhemispheric integration of information. Identifying that hemispheric specialisation of function may be regarded as relative rather than absolute, they suggest that the integration of resources from both hemispheres may increase the overall computational power of the brain in visual processing tasks (for a review, see Banich, 1998).

In order to assess the role of hemispheric integration in the BFA, Banich and colleagues (e.g. Banich & Belger, 1990; Belger & Banich, 1992, 1998; Weissman & Banich, 2000) conducted a series of letter matching tasks which equated the perceptual load across all displays (for an illustration, see Figure 1.2). In doing so, they suggest that the BFA observed may be attributed to the callosal transfer of information, rather than due to differences in perceptual load within and across hemifields (for a discussion, see Weissman & Banich, 2000). Supporting a role of callosal transfer in the BFA, a number of studies have shown that the speed of information transfer across hemispheres significantly correlates with the size of the BFA (Brown & Jeeves, 1993; Cherbuin & Brinkman, 2006; Larson & Brown, 1997) revealing a larger BFA with faster transmission time.

However, Banich and colleagues (e.g. Banich & Belger, 1990; Belger & Banich, 1992, 1998; Weissman & Banich, 2000) highlight that the transfer of resources and information across the corpus callosum can be a costly process. Not only may it increase overall processing time, but information may also be lost or degraded as a

result of transfer. Subsequently, their hypothesis suggests that in order to observe a BFA, tasks must be sufficiently complex so that the costs of hemispheric integration are outweighed by the benefit of extra computational power.

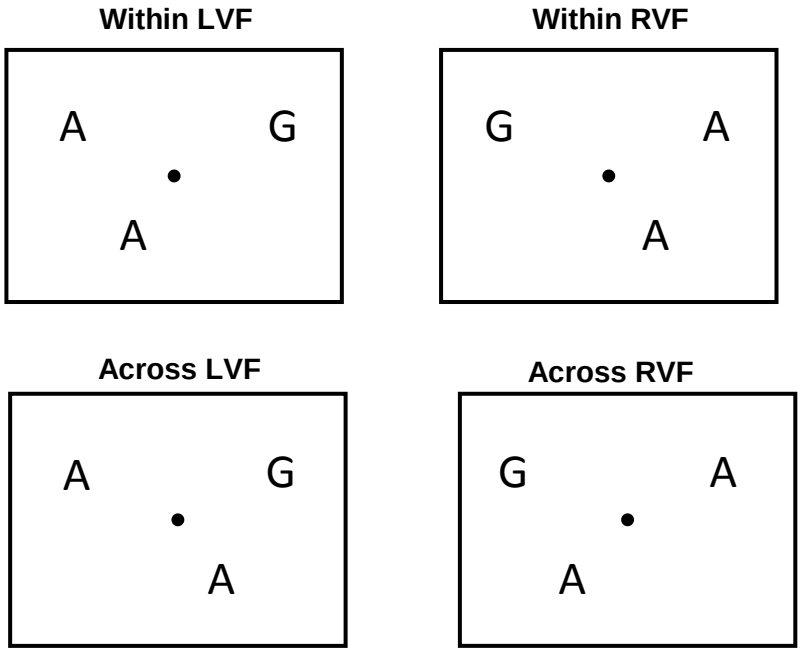

Figure 1.2: An illustration of the within and across hemifield displays used in Banich and colleagues' letter matching tasks (adapted from Weissman & Banich, 2000). Participants were required to identify whether the probe (presented below fixation) matched either of the two stimuli in the left visual field (LVF) or right visual field (RVF).

Demonstrating a role of complexity in the BFA, a number of perceptual matching tasks have shown that the BFA is constrained by the number of processing steps required to complete the task (e.g. Banich & Belger, 1990; Belger & Banich, 1992, 1998; Weissman & Banich, 2000). For instance, whereas those studies revealed no BFA when participants were asked to match letters on the basis of physical appearance (e.g. b and b), the BFA emerged when the letters were matched on the basis of letter name (e.g. B and b). Similarly, Banich and Belger (1990) reported a BFA when participants were required to summate or order numerical digits but not

when they were required to simply match digits on the basis of physical appearance.

Studies have also shown that increasing the number of stimuli to be processed can promote a BFA (Belger & Banich, 1992, 1998; Merola & Liederman, 1990). For instance, Banich and colleagues discovered that the BFA emerged in their physical identity letter matching task (e.g. b and b) when the number of letters to be compared was increased from three to five (Banich & Belger, 1990; Belger & Banich 1992, 1998). Delvenne and colleagues (2011a) also reported that the BFA in their visual enumeration task was contingent on the number of stimuli to be enumerated. Although no hemifield effects were observed when enumerating 1-4 items, the BFA emerged consistently when enumerating 5-8 items.

Research suggests that the benefit of interhemispheric integration and thus the BFA may also be determined by the extent to which unilateral resources can cope with the task demands (e.g. Banich & Belger, 1990). Supporting this possibility, Banich and colleagues observed a unilateral field advantage (UFA) when letter matching tasks which usually exhibit a BFA are reduced in complexity. Specifically, they discovered a UFA when the number of stimuli to be compared was decreased (Banich & Belger, 1990; Belger & Banich, 1992, 1998). In addition, Butcher and Cavanagh (2008, 2012) observed a UFA when participants were required to perceptually match stimuli on the basis of characteristics such as colour and size. They suggest that the UFA can be observed since unilateral resources are better tailored to support low-level perceptual grouping relative to bilateral resources (Pillow & Rubin, 2002). Therefore, when unilateral resources are not taxed and thus the benefit of hemispheric integration is reduced, research suggests that performance in unilateral conditions may even exhibit an advantage over bilateral processing conditions (Banich & Belger, 1990; Butcher & Cavanagh, 2008).

Neuroimaging research examining the neural basis of the BFA in letter matching tasks (Pollman, Zaidel, & Von Cramon, 2003) has indeed supported this notion. Pollman and colleagues (2003) showed that complex matching tasks produce activity consistent with taxed unilateral resources and the engagement of hemispheric resource sharing. The BFA as a response to the demands on unilateral processing may also explain why age effects have been observed in the BFA (Guzzetti & Daini, 2014; Reuter-Lorenz & Stanczak, 2000; Reuter-Lorenz, Stanczak, & Miller, 1999). Those studies reported that older adults exhibited a BFA in less complex tasks relative to younger adults. Consistent with the role of taxed unilateral resources in the BFA, neuroimaging research indicates that older adults recruit bihemispheric resources in tasks which produce lateralised activity in younger adults (e.g. Reuter-Lorenz et al., 2000). The findings may reflect the engagement of a bilateral compensatory mechanism in response to age associated neural decline (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz et al., 2000).

Therefore, with reference to the aforementioned research, it can be identified that the BFA is anything but a stable effect in visual processing. Instead, the BFA may be regarded as a highly dynamic effect which is influenced by the nature of the task. Furthermore, the mechanisms underlying the BFA may involve the parallel processing of independently controlled hemispheric resources (e.g. Alvarez & Cavanagh, 2005) and interhemispheric integration (e.g. Banich, 1998). At present, those two mechanisms have not been distinguished and remain possible explanations the BFA. One factor which may determine the mechanism at work is the stage of visual processing predominately engaged by the task, with perhaps only early visual processes, such as attentional selection, exhibiting parallel hemispheric processing (Alvarez & Cavanagh, 2005; Delvenne, 2005).

However, from the research previously discussed, it is evident that the demonstrations and explanations of the BFA have been drawn from tasks which are especially dominated by perceptual processing. For example, a number of those

tasks required perceptual matching (Banich & Belger, 1990), attentional tracking (Alvarez & Cavanagh, 2005) and visual search (Luck et al., 1989). Therefore, it may be questioned whether higher-level processes such as visual memory are also subject to similar hemifield effects.

Although remaining a relatively limited area of research, studies have suggested that the BFA may also occur in visual memory processing (e.g. Delvenne, 2005; Umemoto, Drew, Ester, & Awh, 2010). Specifically, those studies have indicated that the number of items that can be maintained in visual short-term memory (VSTM) can be increased when the items are distributed across the two visual fields. As a result, this finding may have strong implications for our understanding of VSTM, which as previous research suggests (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), is highly constrained in the number of items that can be simultaneously maintained. The observance of the BFA raises the possibility that previous estimates of VSTM capacity, based on stimulus displays that were not constrained by hemifield alignment (Luck & Vogel, 1997; Vogel et al., 2001), may need to be revisited.

However, despite those demonstrations of the BFA, this hemifield effect has not been consistently shown across all VSTM tasks (Delvenne, 2005; Delvenne, Kaddour, & Castronovo, 2011b; Mance, Becker, & Lui, 2012) . Therefore, those studies strongly question the mechanisms of the BFA in VSTM processing. In the following sections, demonstrations and explanations of the BFA in visual memory processing are discussed.

1.2 Visual short-term memory and the bilateral field advantage

1.2.1 Measuring the capacity of visual short-term memory

Visual short-term memory (VSTM) is a store which allows humans to temporarily hold representations of visual information from the extrapersonal world. Specifically, the VSTM system maintains representations of visually processed information once removed from view, and for that reason, is regarded as a crucial component in the execution of many cognitive tasks (Alvarez & Cavanagh, 2004; Brady, Konkle, & Alvarez, 2011; Delvenne, 2012; Vogel et al., 2001). Despite the VSTM system having a limited storage capacity of only 3-4 items (Luck & Vogel, 1997; Vogel et al., 2001), research suggests that those items can be maintained for several seconds (Zhang & Luck, 2009). Thus, VSTM is distinct from iconic memory, which despite exhibiting a much larger storage capacity, is extremely short-lived with representations lasting in the order of milliseconds (Phillips, 1974).

In order to quantify the storage capacity of VSTM, the change detection paradigm, firstly demonstrated by Phillips (1974), is frequently employed (e.g. Alvarez & Cavanagh, 2004; Delvenne & Bruyer, 2004; Luck & Vogel, 1997). This paradigm requires participants to identify a change between two successively presented visual arrays. In order to assess VSTM, a blank retention interval of at least one second is inserted after the first array in order to allow the transfer of information into VSTM. The ability to identify a change in the second array is used as an indication of whether the items in the first array were successively encoded and stored. In order to understand the amount of information stored, accuracy analyses are typically subject to further quantification using specific formulae such as Cowan's K (Cowan, 2001) which estimates the number of items held in VSTM. The change detection paradigm may also be implemented whilst measuring the capacity

of VSTM electrophysiologically (e.g. Vogel & Machizawa, 2004) which has also provided support for a VSTM capacity limit of 3-4 items.

Whereas this simple change detection task, which involves a recognition judgement at test, may be used to indicate the number of items stored in VSTM, studies have also assessed the resolution (or precision) of VSTM representations by solely changing the requirements at the test phase (Anderson, Vogel, & Awh, 2011; Bays & Husain, 2008; Emrich & Ferber, 2012; Umemoto et al., 2010; Wilken & Ma, 2004; Zhang & Luck, 2008, 2009). For instance, Zhang and Luck (2008) asked participants to recall rather than recognise the colour of a stimulus previously encoded. In order to make a response, participants indicated the position of the colour on a continuous colour wheel. The deviation in responses from the true value was used to estimate not only the probability of storage but also the precision or resolution of the representations held in VSTM. Using this procedure, the study revealed that VSTM capacity is also influenced by the resolution of representations.

Alongside the number and resolution of items in VSTM, the change detection task and recall procedures have allowed an extensive list of variables to be explored. For instance, factors such as the perceptual complexity of objects (Awh, Barton, & Vogel, 2007; Eng, Chen, & Jiang, 2005; Gao et al., 2009, 2011; Xu & Chun, 2006), the number of object features (Delvenne & Bruyer, 2004; Luck & Vogel, 1997; Luria & Vogel, 2011; Olson & Jiang, 2002; Vogel et al., 2001; Wheeler & Treisman, 2002), the number of object locations (Ikkai, McCollough, & Vogel, 2010; Lee & Chun, 2001; Wang, Most, & Hoffman, 2010), the spatial configuration of objects (Boduroglu & Shah, 2009; Delvenne, Braithwaite, Riddoch, & Humphreys, 2002; Delvenne & Bruyer, 2006; Jiang, Olson, & Chun, 2000) and the influence of stimulus dimension (such as colour or shape) (Delvenne & Bruyer, 2004; Gao et al., 2009; Luria, Sessa, Gotler, Jolicoeur, & DellAcqua, 2010; Wheeler & Treisman, 2002; Woodman & Vogel, 2008) have been studied.

However, despite the many factors and variables investigated, the effect of the spatial distribution of items within and across hemifields is a relatively neglected area of research, with only three studies directly assessing the possibility of a BFA in VSTM (Delvenne, 2005; Delvenne et al., 2011b; Umemoto et al., 2010). As previously discussed, the majority of studies which report the BFA have employed attentional processing tasks which limit the involvement of VSTM (e.g. Alvarez & Cavanagh, 2005). Nevertheless, the neuroanatomical and functional relationship between attention and VSTM (Awh & Jonides, 2001) may support the possibility that the BFA also extends to VSTM processing (Delvenne, 2005, 2012; Umemoto et al., 2010).

1.2.2 Reasons to expect a bilateral field advantage in visual short-term memory

Delvenne (2012) suggests that the BFA may also occur during VSTM processing due to similarities in the neural activity elicited during perceptual processing and VSTM maintenance. For instance, studies have demonstrated that neural activations during VSTM encoding are also sustained during VSTM maintenance (Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009; Xing, Ledgeway, McGraw, & Schluppeck, 2013). In addition, studies have highlighted that attention and working memory share a similar neural circuitry relying on frontal and parietal sites (for a review, see Awh & Jonides, 2001) and also share a capacity limit of 3-4 items (Cavanagh & Alvarez, 2005; Luck & Vogel, 1997; Oksama & Hyönä, 2004; Pylyshyn & Storm 1988; Vogel et al., 2001).

Correspondingly, a strong functional relationship between attention and VSTM has also been identified (e.g. Awh & Jonides, 2001), suggesting that hemifield effects within attentional processing may subsequently impact the storage of items in VSTM. For instance, research suggests that the deployment of attention during VSTM encoding supports the transfer of information into the VSTM store (Botta,

Santangelo, Raffone, Lupiáñez, & Belardinelli, 2010; Griffin & Nobre, 2003; Makovski & Jiang, 2007; Murray, Nobre, & Stokes, 2011; Schmidt, Vogel, Woodman, & Luck, 2002). Specifically, those studies revealed that attending to object locations before encoding subsequently improved VSTM recall. Furthermore, research suggests that spatial attention is deployed to object locations during VSTM maintenance to facilitate rehearsal (Awh, Jonides, & Reuter-Lorenz, 1998; Williams, Pouget, Boucher, & Woodman, 2013). Supporting this possibility, the disruption of attentional shifts to relevant locations during the retention interval has been found to reduce memory for both spatial (Awh et al., 1998) and identity (Williams et al., 2013) information.

Models of memory processing also provide support for an important role of attention in memory processing. Specifically, state based models propose that relevant items in a memory task are maintained in an active state by encompassing those items within the focus of attention (Cowan, 1995; McElree, 1996; Oberauer, 2002). In this light, the focus of attention within memory has been likened to attention in perception (Oberauer, 2002) which selects relevant information in the environment for further processing. In addition, those models also posit that previously attended items may remain accessible for later use in an activated long-term memory store. Indeed, a recent review of cognitive neuroscience research supports a distinction in the representational states of items held within and outside the focus of attention (LaRocque, Lewis-Peacock & Postle, 2014).

Cowan (1995) suggests that approximately four chunks of information can be maintained within the focus of attention, corresponding to the capacity estimates of both attention and VSTM obtained in other studies (Cavanagh & Alvarez, 2005; Luck & Vogel, 1997; Oksama & Hyönä, 2004; Pylyshyn & Storm 1988; Vogel et al., 2001). Therefore, it may be suggested that the capacity limits of VSTM processing may be incurred due to this attentional mechanism. In contrast, other state based models propose that attention may be deployed as a narrower single focus, which

selects on an individual item basis (McElree, 1996; Oberauer, 2002). Correspondingly, the limits in attentional switching, which have shown to increase with set size (Oberauer, 2002), may also impede on VSTM processing. However, as discussed further in this thesis, the distribution of the attentional focus and the ability to divide attention to non-contiguous locations is still a matter of debate (for further discussions, see pages 25-27; 115-117).

Alongside the relationship between attention and VSTM, a BFA in VSTM may also be expected given that the contralateral organisation of the early visual system, which is likely to underlie a BFA, may also extend within VSTM processing (Delvenne, 2012). For example, a number of electrophysiological studies have highlighted that the number of items maintained in VSTM can be tracked online by the contralateral hemisphere with respect to the hemifield in which the items were encoded. This activity, also known as contralateral delay activity (CDA), has been found to be a reliable predictor of the number of items recalled in change detection tasks (Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005).

Furthermore, studies have also identified a contralateral activity during visual memory retrieval which is indicative of the hemifield in which the retrieved items were initially encoded (Eimer & Kiss, 2010; Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicoeur, 2012; Gratton, Corballis, & Jain, 1997). For instance, Fautier-Gauthier and colleagues (2012) presented participants with a memory array consisting of laterally presented oriented stimuli. After a retention interval of one second, a single probe stimulus was presented in the centre of the screen. The colour of the probe matched one of the previous stimuli in the memory array and participants were required to recall the orientation of that stimulus. During retrieval, they observed a lateralised brain activity that was indicative of the hemifield in which the relevant stimulus was presented in the memory array. The emergence of this lateralised activity despite the central presentation of the test stimulus has also

been shown in previous studies (Eimer & Kiss, 2010; Gratton et al., 1997) and strongly suggests that hemifield representations can be maintained in VSTM.

1.2.3 Demonstrations of a bilateral field advantage in visual short-term memory

Acknowledging the similarities between attention and VSTM and the possibility of a contralaterally organised memory system, Delvenne (2005) provided the first investigation of the BFA in VSTM processing. Using a change detection task, Delvenne (2005) required participants to memorise the spatial locations of four, six or eight briefly presented squares (200ms) that were presented within a single hemifield or divided equally between hemifields. The display was also divided into four invisible quadrants so that the stimuli were presented equally in the upper or lower quadrants in across hemifield conditions, and in the left or right quadrants in single hemifield conditions (see Figure 1.3).

Delvenne (2005) observed that participants could remember more locations when the items were presented across hemifields relative to within a single hemifield, revealing a significant BFA. Supporting a role of information load in the BFA (Belger & Banich, 1992, 1998; Merola & Liederman, 1990), the findings revealed that the BFA was absent with four items but increased in magnitude with the number of items presented. However, despite a performance advantage in across hemifield conditions, Delvenne's (2005) findings do not support the existence of completely independent hemispheric resources (see Alvarez & Cavanagh, 2005). Instead, the findings indicated only an advantage of bilateral processing relative to unilateral processing in VSTM.

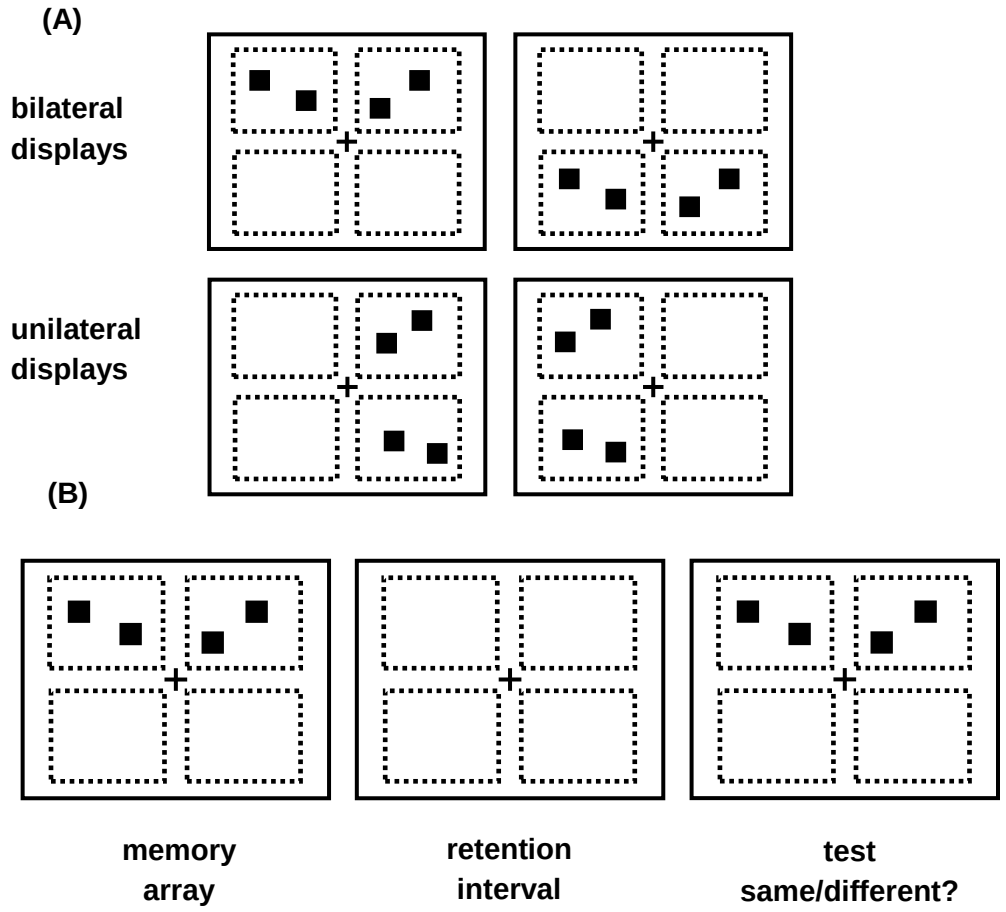

Figure 1.3: An illustration of the displays (A) and trial procedure (B) of Delvenne's (2005) location change detection task. The dotted lines mark the quadrants of the display and were not visible in the experiment. Participants were required to remember the locations of the black squares in the memory array. After a retention interval of one second, participants indicated whether the locations of the squares were the same or different relative to their appearance in the memory array.

Supporting a BFA in VSTM, Umemoto and colleagues (2010) revealed a BFA when participants were required to remember the spatial orientations of two teardrop shaped stimuli (see Figure 1.4). Using a recall procedure which required participants to manually adjust a test stimulus to its previously memorised orientation, the findings revealed that the BFA was influenced by the number of items stored rather than the resolution of those items in VSTM. Furthermore, Umemoto and colleagues (2010) suggest that the BFA cannot be accounted for by differences in VSTM encoding efficiency within and across hemifields, since the BFA still emerged when the stimuli were displayed sequentially, one hemifield at a

time. Therefore, on the basis of those findings, they suggest that the BFA may specifically occur within VSTM storage.

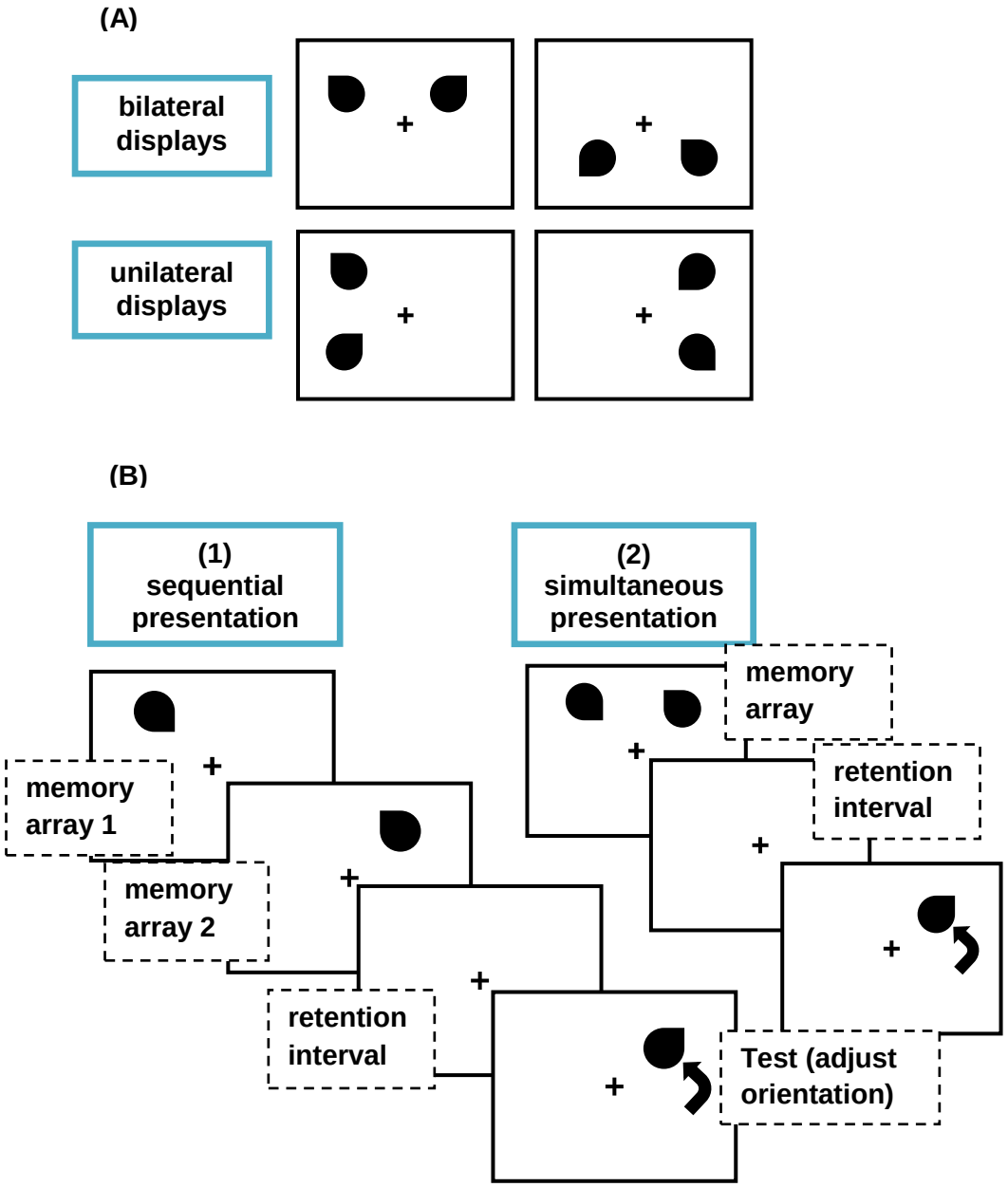

Figure 1.4: An illustration of the displays (A) and trial procedures (B) in Umemoto and colleagues' (2010) orientation memory task. Participants were required to remember the orientations of two teardrop stimuli presented sequentially (1) or simultaneously (2). After a retention interval, participants were required to adjust the orientation of the test stimulus to match the orientation of the relevant stimulus in the memory array.

However, despite the demonstrations of a BFA in VSTM for spatial locations (Delvenne, 2005) and orientations (Umemoto et al., 2010), several studies have failed to reveal a BFA in VSTM when memorising colours (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012). Regardless of testing the same subjects and using the same experimental paradigm, Delvenne (2005) failed to reveal any evidence of a BFA when participants were required to remember the colours of the squares rather than their locations. Instead, across all set sizes (sizes 4, 6 & 8), equivalent performance was shown whether or not the stimuli were divided between the hemifields.

In a recent study which primarily assessed VSTM consolidation of colours, Mance and colleagues (2012) also revealed no hemifield effects in a change detection task requiring memory for two colours that were presented either sequentially or simultaneously. In addition, by directly monitoring VSTM maintenance of colour electrophysiologically through the CDA (Vogel & Machizawa, 2004), Delvenne and colleagues (2011b) revealed that VSTM capacity was simply influenced by the number of items encoded regardless of their distribution across hemifields. Specifically, the CDA revealed a capacity limit of four items in both single hemifield and across hemifield conditions. The corroboration of evidence from electrophysiological measures suggests that the absence of a BFA in colour VSTM may not be attributed to a lack of sensitivity in the change detection paradigms employed, as previously proposed by Umemoto and colleagues (2010).

Drawing upon the early explanations of a BFA in perceptual matching tasks (e.g. Banich & Belger, 1998), Delvenne (2012) also suggests that the absence of a BFA for colour is unlikely to be a direct effect of task complexity. Despite Delvenne (2005) revealing an increase in the magnitude of the BFA for spatial locations with increasing set size, Delvenne (2012) identified that performance in the colour task was lower on average, suggesting a higher level of complexity relative to the spatial task. Therefore, if complexity played a direct role, it might be expected that a BFA in

colour VSTM would also emerge (Delvenne, 2012). Nevertheless, two additional hypotheses of the BFA provided by Alvarez and Cavanagh (2005) remain possible. Instead of task complexity, those hypotheses suggest that the BFA might be constrained by the type of stimuli that are processed and/or by the engagement of attentional selective processes.

1.2.4 Explanations of the bilateral field advantage in visual short-term memory

1.2.4.1 The stimulus domain hypothesis

In order to account for the observance of a BFA in their attentional tracking task and the absence of a BFA in previous visual search tasks (Luck et al.,1989, 1994), Alvarez and Cavanagh (2005) suggest that the BFA might be constrained by the stimulus properties that are processed when performing a task. For instance, it is evident that the ability to attentionally track moving objects is likely to predominately rely on the processing of spatial information, whereas searching for a target on the basis of featural information is likely to be especially dominated by the ability to process object identities (Alvarez & Cavanagh, 2005). For that reason, they suggest that the BFA may only be observed when processing stimuli in the spatial domain. Highlighting the existence of separate visual processing streams in the brain for identity information (the ventral stream; extending occipto-temporal regions) and spatial information (the dorsal stream; extending occipito-parietal regions) (Ungerleider & Mishkin, 1982), Alvarez and Cavanagh (2005) suggest that a dissociation between those two types of processing in the BFA may be plausible.

Similarly, identifying that location and colour VSTM can also be categorised as types of spatial and identity processing respectively, Delvenne (2005) suggests that a BFA for spatial locations but not for colours may also be explained due to a distinction between those stimulus domains. In a review of evidence supporting this account, Delvenne (2012) highlights that the distinction between the stimulus

domains may also extend to memory processing, with a number of studies revealing a dissociation between spatial and identity processing in working memory at both a neuroanatomical (e.g. Ventre-Dominey et al., 2005) and behavioural (e.g., Darling, Della Sala, & Logie, 2009) level. Furthermore, Delvenne (2012) suggests that the BFA may only occur within the spatial domain since spatial processing, which can be primarily localised in the parietal cortex, recruits retinotopically-coded neurons and thus maintains a contralateral organisation which may support a BFA in memory. On the other hand, evidence for the contralateral organisation of the temporal cortex which is involved in ventral stream processing is less clear (for a discussion, see Delvenne, 2012). Supporting this point, a recent study has revealed that the contralateral organisation of visual memory is not an obligatory feature of VSTM processing and instead may depend on the spatial requirements of the task (Vicente-Grabovetsky, Carlin, & Cusack, 2014).

The BFA as a feature of spatial processing may also explain why a BFA was observed in Umemoto and colleagues' (2010) orientation VSTM task. Despite orientations being usually regarded as a featural object property, research suggests that orientation change detection tasks may also be performed by processing the spatial characteristics of the stimuli. For example, recent studies have shown that changing the orientation of an object in a visual multi-objects display affects the whole spatial configuration of the display (Delvenne, Braithwaite, Riddoch, & Humphreys, 2002; Delvenne & Bruyer, 2006) in a similar manner to changing the location of an object (Jiang et al., 2000). Therefore, an orientation change in a change detection task may be signalled by a spatial configuration change. Although Umemoto and colleagues (2010) revealed a BFA with a single probe at test, it is possible that a similar spatial memory strategy was employed since an orientation change also altered the precise location occupied by the stimulus.

However, despite an established dissociation between spatial and identity processing in the brain (Ungerleider & Mishkin, 1982) and an association between

spatial processing and the BFA (e.g. Delvenne, 2005), this simple account based on stimulus domain may not provide a complete explanation for all demonstrations of the BFA. For example, as previously discussed, a number of non-mnemonic studies have also revealed a BFA even though those tasks place fundamental demands on the perceptual matching (e.g. Belger & Banich, 1992; Compton, 2002) and detection (e.g. Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009) of identity information.

Rather than identifying limits in the domain of stimulus processing per se, a number of non-mnemonic tasks have suggested that limits in attentional processing within and across hemifields may account for the BFA (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). Specifically, those findings suggest that the BFA may be constrained by the ability to attentionally select stimuli at encoding, supporting Alvarez and Cavanagh's (2005) second hypothesis which suggests that the BFA is a signature of attentional selection.

1.2.4.2 The attentional selection hypothesis

The ability to attend to relevant objects in a visual scene relies on the engagement of attentional selective processing. Alvarez and Cavanagh (2005) define attentional selection as the first process in a series of capacity limited operations in visual processing preceding higher level stages, such as identification and memory storage. Since their attentional tracking task produced results that were reflective of independent attentional capacity within each hemisphere, they suggest that the BFA might be a signature of attentional selective processes. For that reason, they propose that in order to observe a BFA, attentional selection must be predominately engaged. In relation to previous VSTM findings, revealing a BFA for spatial locations (Delvenne, 2005) and orientations (Umemoto et al., 2010) but not for colour (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), this

hypothesis suggests that attentional selection may be especially dominant in spatial tasks relative to identity tasks.

In line with this possibility, a number of non-mnemonic tasks have demonstrated that the BFA in identity processing tasks is constrained by the demands on attentional selection, and thus only emerges once those demands are increased (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). Specifically those studies, which required participants to perceptually match (Reardon et al., 2009), identify (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009), or detect (Reardon et al., 2009) two stimuli, only revealed a BFA when participants were required to select the stimuli from an array of distracters on the basis of spatial cues at encoding. When the distracters were removed from the array, no hemifield effects were shown.

Therefore, non-mnemonic studies suggest that attentional selective processing during the encoding stage may explain the BFA in VSTM. As previously discussed, given the relationship between attention and memory, it is plausible that the engagement of attentional resources during encoding can influence the storage of information in VSTM (e.g. Schmidt et al., 2002). However, it may be questioned how the attentional selection hypothesis can account for the findings of Umemoto and colleagues (2010) which highlight that the source of the BFA was within VSTM storage rather than during the encoding stage.

Nevertheless, with evidence of spatial selective attention acting as a rehearsal mechanism in VSTM (Awh et al., 1998; Williams et al., 2013), Umemoto and colleagues (2010) also propose that the BFA may arise from the engagement of spatial selective attention within storage. Supporting the engagement of attentional selective processes in VSTM maintenance, a number of additional studies have revealed that orienting attention to the locations previously occupied by visual stimuli can subsequently improve VSTM for those stimuli (e.g. Berryhill, Richmond,

Shay, & Olson, 2012; Delvenne, Cleeremans, & Laloyaux, 2010; Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsein & Nobre, 2006; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Veraca, 2007; Nobre et al., 2004; Tanoue & Berryhill, 2012; Tanoue, Jones, Peterson, & Berryhill, 2013, amongst others). Matsurka and colleagues (2007) suggest that the engagement of selective attention during the retention interval may exert those effects by protecting items from degradation during maintenance.

In order for the attentional selection hypothesis to fully account for the BFA, it also relies on the contention that the distribution of attentional resources is better across hemifields relative to within hemifields (Alvarez & Cavanagh, 2005). Supporting this possibility, a number of studies both behavioural (Awh & Pashler, 2000; Kraft et al., 2005) and electrophysiological (Malinowski, Fuchs, & Muller, 2007) have suggested that spatial attention can be divided more easily across hemifields. For instance, Awh and Pashler (2000) revealed that directing attention to two non-contiguous locations improved processing at those locations, but not at the locations that lay in between. This effect was greater when the attended locations were divided between the hemifields relative to when displayed within a single hemifield. Whilst a single focus of attention may have predicted the stimuli between the two attended regions to also be processed (Erikson & St James, 1986), Awh and Pashler's (2000) findings suggest the existence of a multifocal attentional mechanism that can be divided to at least two non-contiguous locations.

However, although the deployment of multifocal attention plays a predominate role in some explanations of the BFA (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009) it is evident that the ability to divide the attentional focus is still a matter of debate (for a review, see Jans, Peters, & De Weerd, 2010). As a result, in order to explain the BFA, Jans and colleagues (2010) suggest that more resources across hemifields may not necessarily lead to the division of the

attentional focus. Alternatively, they propose that the resources may be integrated within a single focus of attention. Highlighting the flexible nature of spatial attention, they suggest that the focus of attention may be shaped in a way that can process targets whilst ignoring distracters, forming a ring-shaped or curved distribution.

A single focus of attention has also been described in serial shifting theories of attention (e.g. Posner, 1980), which posit that the processing of simultaneously presented items requires a unitary focus of attention to be shifted rapidly to each individual item. Therefore, in order to account for the BFA, this form of attentional deployment relies on the capacity to shift attention more efficiently across hemifields relative to within a hemifield. Supporting this possibility, Chakravarthi and VanRullen (2011) have recently revealed a BFA in the time to shift voluntary attention (otherwise known as endogenous attention or sustained attention) using a new subtraction procedure to measure the time to execute attentional shifts. They suggest that the BFA in shift time may be attributed to the planning of attentional shifts, which can be carried out in parallel by each hemisphere. However, on closer inspection, those findings suggest that approximately 250ms is required to shift endogenous attention, corresponding with previous shift times in the range of 150-500ms (for a discussion, see Chakravarthi & VanRullen, 2011). Therefore, this explanation may come into difficulty when explaining the BFA observed in tasks which have required the rapid identification of simultaneously displayed stimuli in less than 100ms (e.g. Awh & Pashler, 2000; Scalf et al., 2007).

Therefore, although previous studies suggest that the BFA might be explained by the engagement of attentional selective processes, the nature of attentional deployment is yet to be clarified. In addition, although the role of attentional selection has been observed in non-mnemonic tasks (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009), it is yet to be investigated within VSTM processing. Nonetheless, the selection hypothesis provides a plausible account of the BFA in VSTM since it is less constrained than the stimulus

domain hypothesis in explaining the BFA across tasks requiring identity processing (e.g. Chakravarthi & Cavanagh, 2009). In addition, this account may also explain the emergence of a BFA at both the encoding and maintenance stages of VSTM processing, since research has identified a facilitatory role of selection during both stages (e.g. Awh et al., 1998; Schmidt et al., 2002).

1.3 Concluding remarks and thesis outline

As previously discussed, despite numerous demonstrations of the BFA within visual processing, hemifield effects in VSTM have been subject to considerably less research. Furthermore, the research that has been carried out has revealed inconsistent evidence of a BFA in VSTM, indicating a BFA for spatial stimuli but not for colours (e.g. Delvenne, 2005). As a result, a main objective of this thesis is to uncover the conditions in which a BFA may arise within VSTM.

Considering the evidence reviewed above, the present thesis will predominately investigate whether the BFA in VSTM is principally constrained by the attentional selective processes engaged as previously proposed (Alvarez & Cavanagh, 2005). In order to investigate this, colour VSTM will be primarily assessed since those tasks have previously failed to reveal a BFA (e.g. Delvenne, 2005). This will allow firm conclusions to be made regarding the role of attentional selection in relation to the stimulus domain hypothesis, which predicts no BFA when processing identity information (Alvarez & Cavanagh, 2005).

In order to provide a comprehensive understanding of the selection mechanism, the following thesis is divided into two main sections. Within Part One, the role of attentional selection in the BFA is investigated during VSTM encoding. Furthermore, this section also explores different types of selective processing as well as the role of stimuli alignment on the BFA.

Since it is evident that attentional selective processes also operate beyond the encoding stage, acting as a rehearsal mechanism within VSTM storage (Awh et al., 1998; Williams et al., 2013), Part Two investigates the nature of the BFA during VSTM maintenance. Specifically, this section explores whether bilaterally encoded items can better survive decay relative to unilaterally encoded items. In doing so, Part Two provides a further understanding of the factors which promote a BFA within VSTM storage and can influence the magnitude of the BFA observed.

Finally, in the closing chapter of this thesis, the overall findings are discussed in terms of the hypotheses previously proposed. Possible explanations for the inconsistency of the BFA across VSTM stimulus domains (Delvenne, 2005; Umemoto et al., 2010) are outlined and further implications for the understanding of the capacity limits and interactions between VSTM and attentional processing are considered.

2 Part One: The BFA during encoding in VSTM

2.1 Overview

Part One investigated whether attentional selective processes at encoding can promote a BFA in VSTM. Across four experiments, colour VSTM was assessed within and across hemifields in change detection tasks. The findings revealed a BFA when participants were required to select targets amidst distracters at encoding on the basis of spatial information (Experiment 1) or a salient feature (Experiment 3). However, no hemifield effects were shown in the absence of those requirements. Further experiments suggest that those effects cannot be attributed to the horizontal alignment of bilateral displays (Experiments 2 & 4) confirming the advantage of processing bilateral visual arrays. The findings therefore suggest that the BFA is not only constrained by the nature of the memory representation but by the attentional selective processes engaged. Possible mechanisms of this effect are subsequently discussed.

2.2 Introduction

As previously discussed in the literature review, research suggests that the BFA observed in perceptually limited processing tasks also extends to VSTM (Delvenne, 2005; Umemoto et al., 2010). However, the BFA has not been consistently demonstrated across all VSTM tasks, revealing a BFA for spatial locations (Delvenne, 2005) and orientations (Umemoto et al., 2010) but not for colours (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012). Indeed, preliminary investigations confirmed the absence of a BFA for colour in change detection tasks.

Across three set sizes (size 2, size 4, size 6), two encoding conditions (sequential, simultaneous) and two types of test array (single probe, whole probe) no hemifield effects were observed (see Appendix). The replication of no hemifield effects in the sequential presentation condition highlights that the absence of the BFA cannot be accounted for by differences in stimulus encoding in bilateral and unilateral conditions. In addition, by replicating the absence of a BFA using a single probe at test, the results suggest that the level of decision noise is also unlikely to account for the absence of a BFA in colour VSTM.

With previous research indicating a dissociation between spatial and identity processing in the brain (e.g. Ungerleider & Mishkin, 1982), it has been suggested that the BFA might be constrained by the type of stimulus domain that is processed (Alvarez & Cavanagh, 2005; Delvenne, 2005). Specifically, the BFA for spatial orientations and locations but not colours, suggests that the BFA may exclusively pertain to the processing of spatial stimuli (Delvenne, 2012). However, as discussed, this hypothesis is unlikely to account for all instances of the BFA in previous non-mnemonic tasks which required stimulus identities to be processed (e.g. Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009).

On closer inspection, it can be identified that those tasks were especially dominated by attentional selective processes. Each study required the selection of target stimuli from distracter stimuli, which were indicated by spatial pre-cues before the stimulus array. Importantly, the BFA was absent when the distracters were removed from the stimulus array and the requirement to select was reduced. Therefore, the findings suggest that the BFA may not only be constrained by the stimulus domain but by the attentional resources engaged. Specifically, it has been suggested that the BFA is a signature of attentional selection (Alvarez & Cavanagh, 2005; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). With reference to previous studies which reveal the possibility of independent attentional resources within each hemisphere (Alvarez & Cavanagh, 2005; Luck et al., 1989, 1994) and the ability to

divide attention more easily across hemifields (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007), the plausibility of an attentional mechanism is strengthened.

In response to this research, Part One of the present thesis investigates whether the BFA in VSTM processing is also constrained by attentional selective processes. Specifically, the following experiments addressed whether the absence of a BFA for colour can be explained by the task demands on selective processing during encoding. In order to investigate this possibility, participants completed a change detection task requiring memory for colours that were distributed within or across hemifields. On some trials, the demands on attentional selection were manipulated by indicating a subset of the array to remember with the use of spatial (Experiment 1) or featural (Experiment 3) cues. If the BFA is constrained by attentional selection, then the emergence of a BFA in VSTM can be expected in those conditions. On the other hand, if the BFA in VSTM is constrained by the stimulus domain, then no hemifield effects may be expected, since the task required memory for colours.

2.3 Experiment 1

2.3.1 Method

2.3.1.1 Participants

Twenty-two subjects completed the experiment (18 females; mean age = 23.50 years; range = 19 - 39 years). Participants were neurologically normal with self-reported correct colour vision and correct or corrected-to-normal visual acuity.

2.3.1.2 Stimuli and procedure

A computer-based change detection task, generated using E-Prime computer software (Psychology Software Tools, www.pstnet.com), was presented on a 17inch screen of a 3.20 GHz PC. All stimuli were presented on a grey screen

background (127 of red, blue, and green phosphors) which was divided into four invisible quadrants. At a viewing distance of approximately 60cm, each quadrant subtended approximately 4.60° x 4.60° and was positioned so that the centre of each quadrant was 3.74° from the horizontal and vertical meridian (see Figure 2.1).

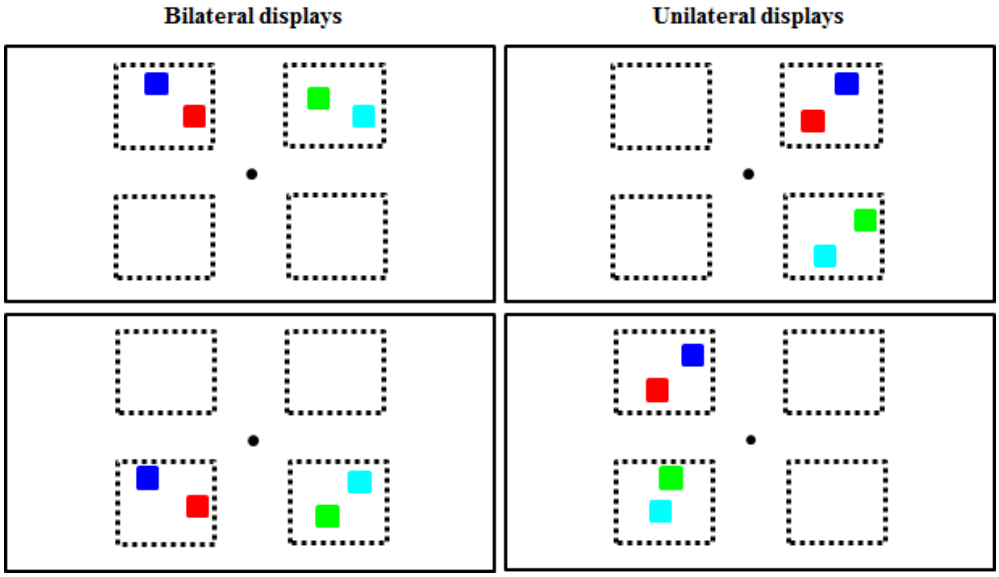

Figure 2.1: The bilateral and unilateral displays used in Experiment 1. The dashed lines mark the quadrants in which the stimuli were presented and were invisible in the experiment. For clarity, the illustration is not drawn to scale.

Each trial commenced upon pressing the space bar and was followed by the presentation of a white fixation dot at the centre of the screen (subtending 0.26° x 0.26°). Participants were instructed to fixate this point throughout the trials. In the distracter conditions, two spatial cues which were shaped as empty squares extending .77° x .77°, were presented within two vertical quadrants or two horizontal quadrants (one cue in one quadrant) for 50ms. The cues were followed by an unfilled cue-to-target delay of 50ms (50% of distracter trials) or 500ms. As previous spatial selection studies which observed a BFA (Awh & Pashler, 2000; Chakravathi & Cavanagh, 2009; Reardon et al., 2009) have exclusively utilised long cue presentation and delay times (> 450ms), the delay was manipulated here to investigate whether the time to deploy attention may influence the observance of the BFA. Previous research suggests that long relative to short delays lead to

higher resolution attentional distributions which are more spatially specific and may better facilitate the orienting of attention to non-contiguous locations (Jans et al., 2010). Therefore, it may be the case that the cue-to-target delay duration may influence selection efficiency and subsequently the BFA.

After the cue-to-target delay, the memory array consisted of four or six coloured squares presented equally across the two horizontal quadrants (bilateral display) or across the two vertical quadrants (unilateral display) that were cued. The coloured squares subtended .77° x .77° separated with a minimum distance (centre to centre) of 1.60°. The colour of each stimulus was randomly selected from one of six highly discriminative colours (blue, green, pink, red, turquoise, and yellow) which were generated using permutations of red, blue, and green phosphors (either 0 or 255 on the scale 0 - 255). A single colour was not repeated within a quadrant, however repetition of colours across quadrants was possible. In the distracter trials, participants were instructed to remember the colours of the two squares that were cued. In the no distracter trials, no spatial cues were presented. In those conditions, participants were instructed to remember all of the coloured squares (see Figure 2.2).

Following the memory array and after a retention interval of 1000ms, a test array was presented. Participants were instructed to indicate as accurately as possible whether there was a change in the colour of the squares relative to their appearance in the memory array. They were also instructed to prioritise accuracy rather than the speed of their response. In 50% of the trials, the colours did not change, whereas in the remaining trials, one square changed colour. The colour of the changed square was selected from a remaining colour not used within the same quadrant. However repetition of colour across quadrants was possible. Participants responded by pressing the appropriate key on the computer keyboard (1 = no change; 2 = change). The next trial began once a response had been made. Throughout each trial, participants were instructed to rehearse a series of three

digits out loud in order to evoke articulatory suppression. The digits were rehearsed at a rate of approximately three digits per second.

As outlined above, the experiment consisted of four possible conditions. There were two distracter conditions, requiring participants to select two targets among two distracters (2 + 2 condition) or four distracters (2 + 4 condition), and two no distracter conditions, requiring memory for four (4 + 0 condition) or six coloured squares (6 + 0). Each condition was tested in a separate block (counterbalanced across participants). There were 96 trials in each distracter condition (48 trials with a 50ms cue-to-target delay and 48 trials with a 500ms cue-to-target delay blocked separately), and 96 trials in each no distracter condition. Within all conditions, 50% of the trials were presented bilaterally and the remaining trials were presented unilaterally. In total, participants completed 384 experimental trials. Prior to each block of trials, participants completed 10 practice trials.

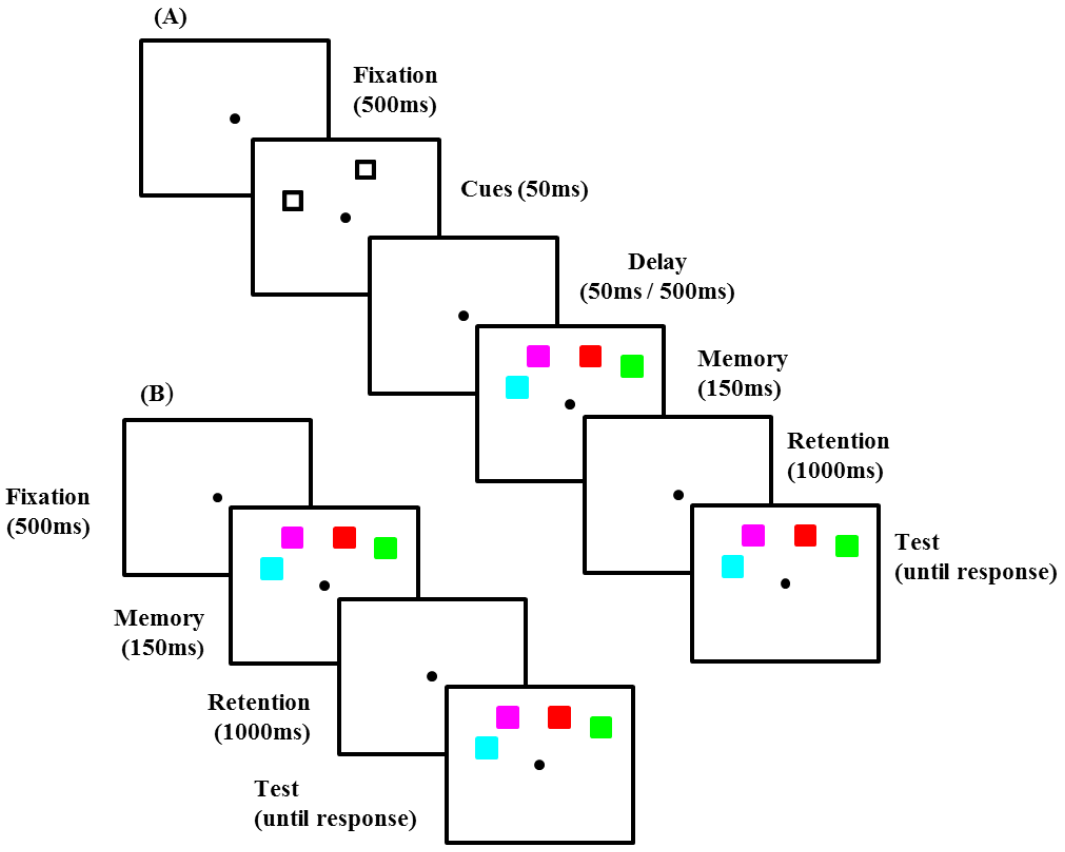

Figure 2.2: The trial procedure for the distracter (A) and no distracter (B) conditions of Experiment 1.

2.3.2 Results

Trials with response times less than 200ms were removed from the data resulting in the exclusion of 0.2% of trials. Mean response accuracy (%) was analysed to assess performance across each condition. However to provide a second representation of the results, A prime[1] (A´) from signal detection theory (Aaronson & Watts, 1987; Grier, 1971; Pollack & Norman, 1964) was also computed.

Throughout the experiments reported in this thesis, response accuracy was the dependent variable of interest as participants were instructed to prioritise accuracy rather than response time. As expected, in the present and subsequent experiments, response times failed to produce consistent significant effects. However, the effects identified throughout the experiments supported the accuracy analyses and the absence of speed-accuracy trade-offs. Therefore, response times will not be reported further.

2.3.2.1 Accuracy

Since the cue-to-target delay varied (50ms or 500ms) in the distracter condition trials (2 + 2; 2 + 4), a preliminary analysis explored whether the cue-to-target delay influenced performance in those conditions. A 2 (cue-to-target delay: 50ms, 500ms) x 2 (condition: 2 + 2, 2 + 4) x 2 (display: bilateral, unilateral) repeated measures ANOVA was conducted. The results revealed an effect of cue-to-target delay [$F(1, 21) = 8.57$, $p < .01$, $\eta_p^2 = .29$] with greater accuracy in the 500ms relative to the 50ms conditions, and a main effect of condition [$F(1, 21) = 15.67$, $p < .002$, $\eta_p^2 = .43$] with greater accuracy in the 2 + 2 relative to the 2 + 4 condition. In addition, a main effect of display was revealed [$F(1, 21) = 5.19$, $p < .05$, $\eta_p^2 = .20$] indicating a

[1] A´ = 0.5 + (x - y)(1 + x - y) / 4x(1 - y) where x is the probability of a hit and y is the probability of a false alarm

significant BFA. However, an interaction between delay and display was also shown [F(1, 21) = 4.73, p < .05, η_p^2 = .18] which highlighted that the BFA was only evident in the distracter conditions with a 500ms cue-to-target delay [t(21) = 3.81, p < .002, *d* = .64]. In the 50ms conditions, no hemifield effects were observed (p = .92). No other interactions were observed (p > .1). Therefore, the following analyses, which specifically assessed the role of selection in the BFA, analysed the distracter conditions with 50ms and 500ms cue-to-target delays separately.

In order to investigate the role of selection in the BFA, distracter and no distracter conditions were compared in a three-way 2 (distracter: no distracters, distracters) x 2 (total set size: four, six) x 2 (display: bilateral, unilateral) repeated measures ANOVA. Including the distracter conditions with a 500ms cue-to-target delay only, the results revealed a main effect of distracter [F(1, 21) = 9.74, p < .01, η_p^2 = .32], a main effect of size [F(1, 21) = 69, p < .001, η_p^2 = .77] and a main effect of display [F(1, 21) = 14.59, p < .005, η_p^2 = .41] . Post hoc analyses revealed that accuracy was greater in conditions with a total set size of four stimuli relative to six stimuli, and in bilateral displays relative to unilateral displays. In addition, accuracy was significantly greater in conditions which required targets to be filtered from distracters (2 + 2, 2 + 4) relative to conditions with no distracters (4 + 0, 6 + 0) suggesting that participants successfully selected targets among distracters. An interaction between distracter and size [F(1, 21) = 24.52, p < .001, η_p^2 = .54] indicated greater accuracy in the 2 + 4 condition relative to the 6 + 0 condition [t(21) = 4.53, p < .001, *d* = 1.06] but no difference between the 2 + 2 and 4 + 0 condition (p = .61). Therefore, the results suggest that distracter conditions were performed better than no distracter conditions when the total set size was increased. In addition, the interaction revealed that accuracy was greater in the 2 + 2 relative to the 2 + 4 conditions, however this difference was marginally significant [t(21) = 1.99, p = 0.06, *d* = .43]. On the other hand, accuracy in the 4 + 0 condition was

significantly greater than accuracy in the 6 + 0 condition [t(21) = 14.56, p < .001, *d* = 1.07].

Importantly, the results showed a significant interaction between distracter and display [F(1, 21) = 6.88, p < .05, η_p^2 = .25], revealing overall, a significant BFA in conditions with distracters (2 + 2, 2 + 4) [t(21) = 3.81, p < .005, *d* = .81] and no difference between bilateral and unilateral displays in conditions with no distracters (p = .83) (4 + 0, 6 + 0; see Figure 2.3). In addition, the interaction supports the possibility that targets were selected from distracters more efficiently when the stimuli were presented bilaterally relative to unilaterally. Although, paired sample t-tests revealed better performance in distracter conditions relative to no distracter conditions across both bilateral [t(21) = 3.52, p < .005, *d* = .79] and unilateral [t(21) = 1.99, p = .06, *d* = .48 *marginally significant*] displays, distracter - no distracter difference scores revealed that the performance advantage in distracter conditions was significantly larger within bilateral conditions relative to unilateral conditions [t(21) = 2.64, p < .02, *d* = .58].

Additionally, no interaction was observed between size and display (p = .93), although a tendency towards a three-way interaction was observed between distracter, size and display [F(1, 21) = 3.96, p = .06, η_p^2 = .16], suggesting a larger BFA in 2+2 relative to 2+4. However, further two-way repeated measures ANOVA's between size (4, 6) and display (bilateral, unilateral) revealed that the BFA in the distracter conditions (2+2, 2+4) and the absence of hemifield effects in the no distracter conditions (4+0, 6+0), did not significantly interact with size (p > .21). In addition, the three-way interaction was not significant in further analysis on A´ (p = .25) and is therefore treated with caution.

The analysis including distracter trials with a 50ms cue-to-target delay failed to replicate such findings. Despite revealing a significant main effect of size [F(1, 21) = 80.93, p < .001, η_p^2 = .79], with accuracy greater in conditions with four stimuli (2 +

2, 4 + 0) relative to six stimuli (2 + 4, 6 + 0), the results showed no effects of distracter or display and no significant interactions (p > .24). A tendency towards an interaction between distracter and size was shown [F(1, 21) = 3.86, p = .068, η_p^2 = .16] suggesting a trend for greater accuracy in the no distracter condition (4+0) relative to the distracter condition (2+2) in size four displays [t(21) = 2.01, p = .057, *d* = .43], whereas no difference between distracter and no distracter conditions was observed in size six displays (p = .17). However, this interaction did not approach significance in further analysis on A´ (p = .26). Given that research has indicated finer spatial resolution within the lower relative to the upper visual fields (He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001) and the existence of hemispheric differences in visual spatial processing (for a review, see Jager & Postma, 2003), visual field asymmetries in performance were also assessed in the no distracter and distracter conditions (500ms, 50ms). However paired sample t-tests revealed no difference between the left versus the right unilateral field trials (p > .19) or between the upper versus the lower bilateral field trials (p > .71), highlighting no visual field asymmetries in task performance.

2.3.2.2 A´

The same analysis was repeated with A´ and the pattern of results was replicated. A 2 (cue-to-target delay: 50ms, 500ms) x 2 (condition: 2 + 2, 2 + 4) x 2 (display: bilateral, unilateral) repeated measures ANOVA indicated that the BFA was only shown in the distracter conditions with a 500ms cue-to-target delay. Specifically, the analysis revealed an effect of cue-to-target delay [F(1, 21) = 5.34, p < .05, η_p^2 = .20], with greater accuracy in the 500ms relative to the 50ms conditions, and a main effect of condition [F(1, 21) = 11.51, p < .005, η_p^2 = .35], with greater accuracy in the 2 + 2 relative to the 2 + 4 conditions. A significant interaction was also shown between those two factors [F(1, 21) = 5.31, p < .05, η_p^2 = .20] indicating that the effect of cue-to-target delay was evident in the 2 + 4 condition [t(21) = 2.96, p < .01,

d = .63] but not in the 2+2 condition (p = .39). Nevertheless, the results revealed an interaction between display and delay [F(1, 21) = 3.88, p = .062, η_p^2 = .16, *marginally significant*] highlighting a significant BFA in the 500ms conditions [t(21) = 2.84, p < .02, *d* = .53] but no hemifield effects in the 50ms conditions (p = .93). No other main effects or interactions were observed (p> .22).

In examining the role of selection in the BFA, a three-way 2 (distracter: no distracters, distracters) x 2 (total set size: four, six) x 2 (display: bilateral, unilateral) repeated measures ANOVA was again conducted twice, with the distracter conditions with different cue-to-target delays (50ms, 500ms) analysed separately. Including distracter trials with a 500ms cue-to-target delay, the results revealed main effects of distracter [F(1, 21) = 4.14, p = .055, η_p^2 = .17, *marginally significant*], size [F(1, 21) = 56.93, p < .001, η_p^2 = .73] and display [F(1, 21) = 7.12, p < .02, η_p^2 = .25]. Post hoc analyses showed that accuracy was greater in conditions with a total set size of four stimuli relative to six stimuli, and in bilateral displays relative to unilateral displays. In addition, accuracy was significantly greater in conditions which required targets to be filtered from distracters (2 + 2, 2 + 4) relative to conditions with no distracters (4 + 0, 6 + 0), suggesting that participants successfully selected targets among distracters. Again, an interaction between distracter and size [F(1, 21) = 27.56, p < .001, η_p^2 = .57] indicated better performance in the 2 + 4 condition relative to the 6 + 0 condition [t(21) = 3.68, p < .002, *d* = .91], however no difference between the 2 + 2 and 4 + 0 was revealed (p = .98). In addition, the interaction also showed that accuracy was greater in the 2 + 2 relative to the 2 + 4 conditions, however this difference was only marginally significant [t(21) = 2.01, p = .057, *d* = .50], whereas performance in the 4 + 0 condition was significantly greater than in the 6 + 0 condition [t(21) = 12.27, p < .001, *d* = 2.82].

Importantly, the results revealed an interaction between distracter and display, [F(1, 21) = 3.71, p = .068, η_p^2 = .15, *marginally significant*], highlighting a significant BFA in conditions with distracters (2 + 2, 2 + 4) [t(21) = 2.68, p < .02, *d* = .57], and no difference between bilateral and unilateral displays in conditions with no distracters (4 + 0, 6 + 0; p = .78) (see Figure 2.3). In addition, paired sample t-tests indicated greater selection efficiency within bilateral displays. The results revealed that performance was significantly greater in distracter conditions relative to no distracter conditions in bilateral displays [t(21) = 2.37, p < .05, *d* = .55], whereas no difference was observed in unilateral displays (p = .36). No other interactions were revealed (p > .25).

The analysis including distracter trials with a 50ms cue-to-target delay revealed a main effect of size [F(1, 21) = 44.92, p < .001, η_p^2 = .68], with increased accuracy in conditions with four stimuli (2 + 2, 4 + 0) relative to six stimuli (2 + 4, 6 + 0). However no other main effects or interactions were revealed (p > .19). In addition, the absence of visual field asymmetries in task performance across bilateral and unilateral trials was confirmed within both the distracter (500ms, 50ms) and no distracter conditions (p > .1).

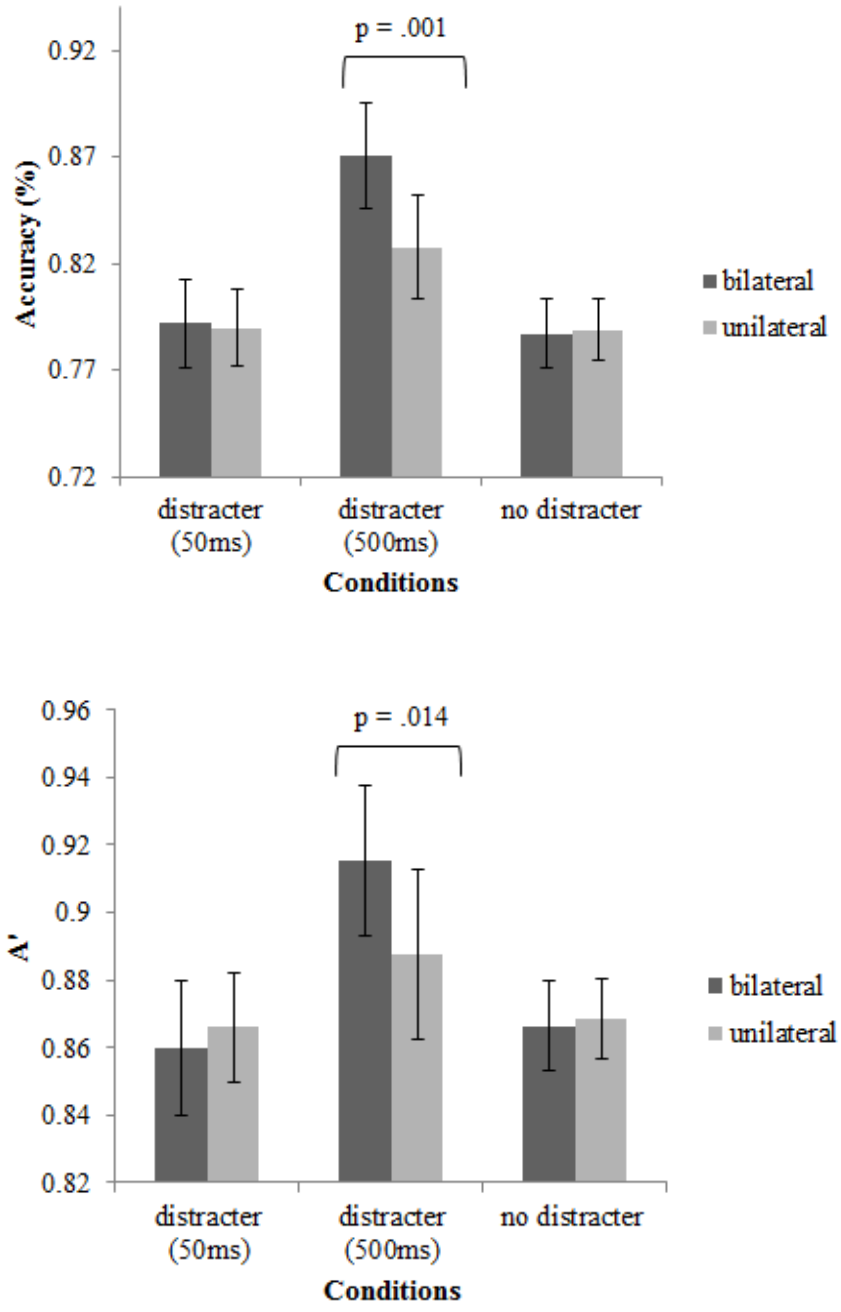

Figure 2.3: The results of Experiment 1. Response accuracy (%) and A´ as a function of condition (distracter 50ms, distracter 500ms, no distracter) and display (bilateral, unilateral). The error bars represent the standard error of the mean values.

2.3.3 Discussion

The aim of Experiment 1 was to investigate whether the absence of a BFA in colour VSTM, consistently shown in previous studies (Delvenne, 2005; Delvenne et al.,

2011b; Mance et al., 2012), can be explained by the task demands on attentional selection at encoding. The results suggest this is the case, revealing a BFA only when those task demands were increased. Specifically, a BFA emerged when participants were required to attentionally select targets from distracters on the basis of spatial pre-cues at encoding. In the absence of those requirements, no hemifield effects were shown.

The results suggest that the presence of the BFA in the distracter conditions was influenced by the cue-to-target delay (500ms, 50ms), revealing a BFA in only the 500ms conditions. Supporting a strong relationship between selection and the BFA, the results suggest that participants failed to efficiently select targets in the conditions with a short cue-to-target delay (50ms). Despite requiring only two targets to be memorised relative to four or six in the no distracter conditions, performance in the 50ms distracter condition did not differ. On the other hand, performance in the 500ms cue-to-target delay distracter condition was significantly greater relative to the no distracter conditions, suggesting that participants efficiently selected the targets from the distracters. Furthermore, a comparison of distracter and no distracter performance within bilateral and unilateral displays suggested that participants selected targets from distracters more efficiently in bilateral conditions. As a result, those findings strongly support the notion of the BFA as a signature of selective processing (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009).

However, in order to confirm the emergence of the BFA in the present study, a further possibility must be addressed. Since the stimuli in the bilateral and unilateral conditions were aligned differently, with bilateral stimuli aligned horizontally and unilateral stimuli aligned vertically, it is possible that the BFA observed reflects an advantage of processing horizontally aligned displays. Indeed, to account for the presence of the BFA, research has highlighted a *directional reading hypothesis* (Boles, 1990) whereby a processing advantage for horizontally aligned stimuli

exists due to horizontally biased attentional strategies established through reading (Heron, 1957).

In order to investigate the contribution of this potential factor, Experiment 2 examined the influence of stimuli alignment on performance in the 2 + 2 distracter condition with a 500ms cue-to-target delay. In order to remove the influence of bilateral and unilateral processing, horizontal and vertical alignment was assessed within one hemifield at a time.

2.4 Experiment 2

2.4.1 Method

2.4.1.1 Participants

Twenty subjects completed the experiment (18 females; mean age = 19.15 years; range = 18 - 20 years). Participants were neurologically normal with self-reported correct colour vision and correct or corrected-to-normal visual acuity.

2.4.1.2 Stimuli and procedure

In order to assess performance across the horizontally and vertically aligned displays of Experiment 1, the four invisible quadrants in the display were presented within a single hemifield (left, right), moving the centre of the quadrants 7.44° to the left or right of fixation (see Figure 2.4). The 2 + 2 condition with a 500ms cue-to-target delay was the only condition to be tested. All other aspects of the trial procedure mirrored Experiment 1 with the exception that the stimuli were cross-shaped. Participants completed 10 practice trials followed by a single block of 96 experimental trials. Once again, participants were instructed to rehearse a series of three digits out loud in order to evoke articulatory suppression.

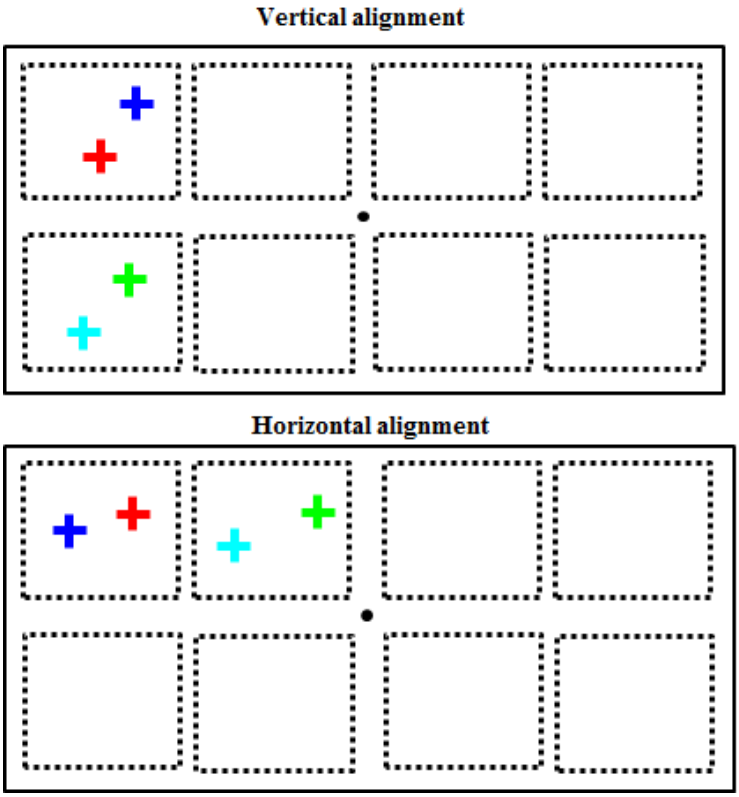

Figure 2.4: An example of the vertically and horizontally aligned displays used in Experiment 2. The stimuli appeared within the left or right hemifields and were aligned across two vertical quadrants (vertically aligned) or across two horizontal quadrants (horizontally aligned). The dashed lines mark the positions of the quadrants and were not visible in the experiment. For clarity, the illustration is not drawn to scale.

2.4.2 Results

Trials with response times less than 200ms were removed from the data resulting in the exclusion of 0.1% of trials. In order to examine the influence of stimuli alignment, response accuracy was analysed in a 2 (hemifield: left, right) x 2 (alignment: horizontal, vertical) repeated measures ANOVA. The results revealed no main effects of hemifield or alignment and no interaction between those factors was shown ($p > .49$). The analysis on A´ also replicated the results ($p > .31$; see Figure 2.5).

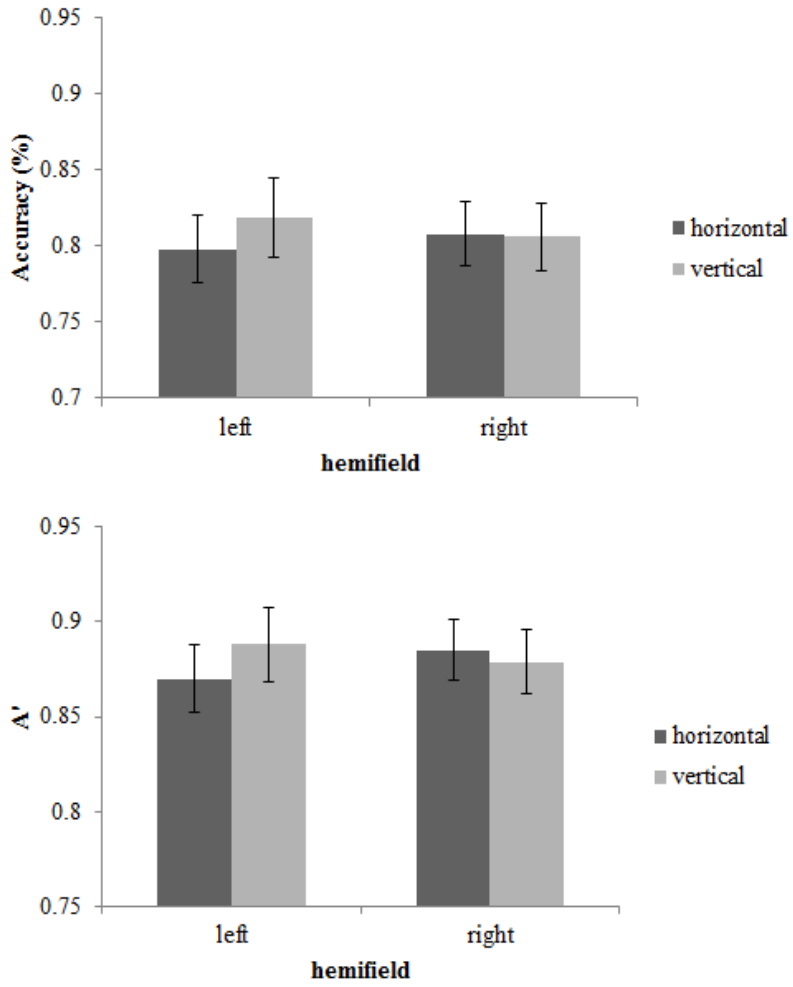

Figure 2.5: The results of Experiment 2. Response accuracy (%) and A´ as a function of hemifield (left, right) and stimuli alignment (horizontal, vertical). The error bars represent the standard error of the mean values.

2.4.3 Discussion

Experiment 2 examined whether the BFA in Experiment 1 can be explained by the alignment of the stimuli in unilateral and bilateral conditions. Specifically, the study investigated whether the BFA in distracter conditions can be accounted for by the processing of horizontally aligned relative to vertically aligned stimuli. The results revealed that the alignment of the stimuli within a single hemifield had no effect on performance. Therefore, the findings strongly suggest that the BFA in the distracter conditions of Experiment 1 can be explained due to bilateral rather than horizontally aligned displays.

The findings of Experiment 1 support previous research which suggests that the selection of targets from distracters can promote a BFA (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). However, a number of studies also suggest that spatial pre-cues can facilitate the transfer of information into VSTM (Botta et al., 2010; Griffin & Nobre, 2003; Makovski & Jiang, 2007; Murray et al., 2011; Schmidt et al., 2002), revealing a recall advantage for stimuli that are cued relative to not cued. Therefore, it may be questioned whether the findings of Experiment 1 can be explained exclusively by the attentional orienting effects of the pre-cues rather than the requirement to filter targets from distracters.

In order to address this possibility, Experiment 3 investigated whether selecting targets from distracters in the absence of the spatial pre-cues can promote a BFA. Thus participants were required to select targets on the basis of a featural difference whereby targets and distracters were differentiated by shape. If the BFA is exclusively driven by the pre-cues then the results were expected to reveal no evidence of a BFA. However, if the BFA is a feature of selecting targets from distracters then the BFA was expected to emerge.

In addition, Experiment 3 matched the number of targets to be processed in the distracter and no distracter conditions. This was not the case in Experiment 1, which raises the possibility that the hemifield effects observed may be attributed to the number of stimuli that were memorised. With previous estimates of a VSTM capacity limit of 3 - 4 objects (Luck & Vogel, 1997; Vogel et al., 2001), the BFA in the distracter conditions with two targets, and the absence of the BFA in the no distracter conditions with four or six targets, may also be the result of under- and over-capacity processing respectively.

Therefore, in order to rule out this possibility, both the distracter and no distracter conditions of Experiment 3 required the processing of two target stimuli, with the exception that two distracters were presented amidst the targets in the distracter

condition. If the BFA can be explained by the processing of two target stimuli, then a BFA may also be expected in the no distracter condition. However, if the BFA can be explained by selection, then the BFA should only arise within the distracter condition.

2.5 Experiment 3

2.5.1 Method

2.5.1.1 Participants

Thirty-four subjects took part in the study (19 females; mean age = 24.1; range = 18 - 38 years). Participants were neurologically normal with self-reported correct colour vision and normal or corrected-to-normal visual acuity.

2.5.1.2 Stimuli and procedure

As in Experiment 1, participants completed a change detection task however the following changes were made. After the presentation of the fixation point (500ms) a memory array was presented for 100ms consisting of either two crosses (no distracter condition) or two crosses and two circles (distracter condition; see Figure 2.6). A review of divided field methodology recommends that displays should be limited to a maximum duration of 180ms to avoid the possibility of eye movements from fixation (Bourne, 2006). Since the number of stimuli was significantly reduced in the no distracter conditions relative to Experiment 1, which required up to six relevant items to be processed, a more conservative display duration of 100ms was employed to further reduce the possibility of eye movements whilst still allowing sufficient time to encode (see Luck & Vogel, 1997). At a viewing distance of approximately 60cm, the crosses and circles subtended .77° x .77° separated with a minimum distance (centre to centre) of 1.92°. The size and position of the invisible quadrants was the same as in Experiment 1. Participants were instructed

to remember only the colours of the crosses and to ignore the colours of any circles that were presented.

As outlined above, the experiment required memory for two targets among two distracters (2 + 2 distracter condition) or two targets with no distracters (2 + 0 no distracter condition). Each condition consisted of 96 trials (48 change trials and 48 no-change trials) resulting in a total of 192 experimental trials which were randomly distributed into two blocks of 96 trials. Within each condition, 50% of the trials were presented bilaterally and the remaining trials were presented unilaterally. Participants completed 20 practice trials to familiarise themselves with the task. Throughout each trial, participants were instructed to rehearse a series of three digits out loud in order to evoke articulatory suppression.

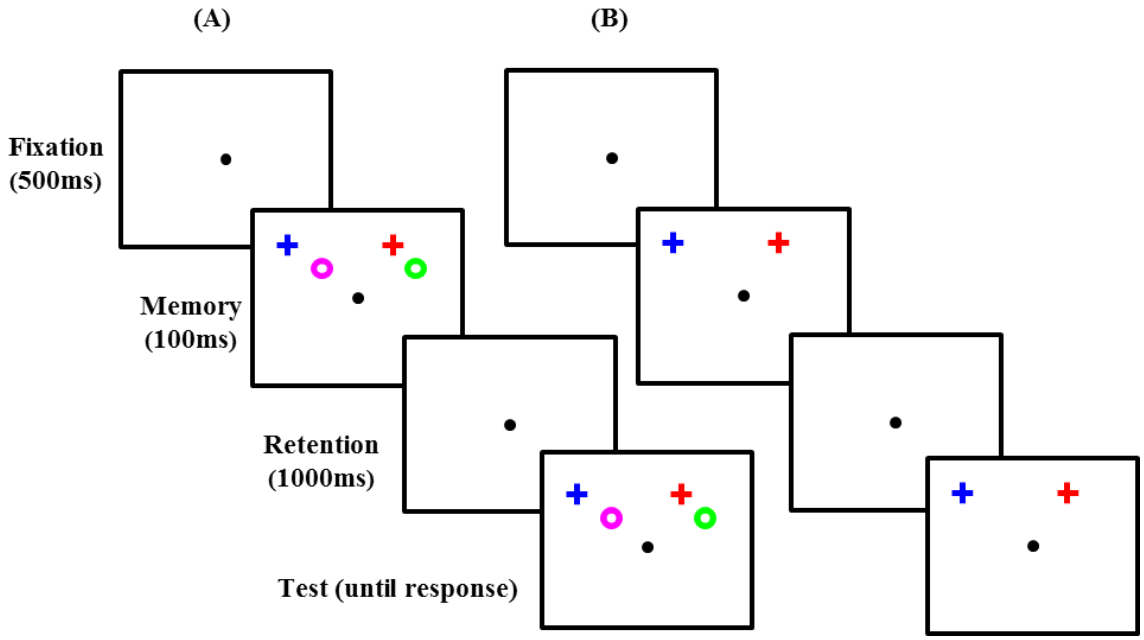

Figure 2.6: The trial procedures of Experiment 3 for the distracter (A) and no distracter (B) conditions. For clarity, the illustration is not drawn to scale.

2.5.2 Results

Trials with response times less than 200ms were removed from the data resulting in the exclusion of less than 0.1% of trials. As shown below, the analysis on response accuracy and A´ revealed a similar pattern of results.

2.5.2.1 Accuracy

Mean accuracy scores were compared in a two-way 2 (distracter: distracters, no distracters) x 2 (display: bilateral, unilateral) repeated measures ANOVA. The results showed a significant main effect of distracter [F(1, 33) = 44.04, p < .001, η_p^2 = .57], indicating greater accuracy in the no distracter condition relative to the distracter condition, and no main effect of display (p = .18). However, an interaction between distracter and display was revealed [F(1, 33) = 3.62, p = .066, η_p^2 = .1, *marginally significant*]. In line with the results of Experiment 1, paired sample t-tests revealed a significant BFA in the distracter condition [t(33) = 2.19, p < .05, *d* = .38, and no difference between bilateral and unilateral displays in the no distracter condition (p = 1; see Figure 2.7).

The interaction also revealed that targets were selected more efficiently in the bilateral relative to unilateral distracter condition. Since both the distracter and no distracter condition required two target stimuli to be remembered, the extent to which performance is similar between those two conditions may indicate how efficiently targets were selected from distracters in the distracter condition. Although performance in the distracter condition was significantly decreased relative to performance in the no distracter condition in both bilateral [t(33) = -5.71, p < .001, *d* = 1.07] and unilateral [t(33) = -6.56, p < .001, *d* = 1.3] displays, the results suggest that this difference was reduced in bilateral displays. Analysis of distracter - no distracter difference scores for each display (bilateral, unilateral) revealed a tendency for a smaller difference score in bilateral relative to unilateral conditions [t(33) = 1.90, p = .066, *d* = .33, *marginally significant*].

As in Experiment 1, visual field asymmetries in task performance within the distracter and no distracter conditions were also assessed across the unilateral (left versus right) visual field trials, and the bilateral (upper versus lower) visual field trials. Although no asymmetries in performance were shown in the no distracter

condition (p > .33), an increase in accuracy was observed within the lower relative to the upper visual field in the distracter condition [t(33) = 2.31, p < .05, *d* = .42]. As previously highlighted, a lower visual field advantage may be explained due to the existence of finer spatial resolution in the lower relative to the upper visual field (He et al., 1996; Intriligator & Cavanagh, 2001).

2.5.2.2 A´

The same analysis on A´ also revealed a main effect of distracter [F(1, 33) = 33.88, p < .001, η_p^2 = .51], with better performance in the no distracter condition relative to the distracter condition, and no effect of display (p = .16). Importantly, a significant interaction was shown between those two factors [F(1, 33) = 4.28, p < .05, η_p^2 = .12]. Paired sample t-tests confirmed a BFA in the distracter condition [t(33) = 2.02, p = .052, *d* = .36, *marginally significant*] however no hemifield effects was shown in the no distracter condition (p = 1; see Figure 2.7).

Furthermore, the interaction also suggests that targets were selected more efficiently in the bilateral distracter condition. Paired sample t-tests revealed that performance in the no distracter condition was greater relative to the distracter condition in both bilateral [t(33) = -5.22, p < .001, *d* = 1.02] and unilateral [t(33) = -5.62, p < .001, *d* = 1.21] displays. However, a significantly smaller distracter - no distracter difference score was observed in bilateral relative to unilateral displays [t(33) = 2.07, p < .05, *d* = .34].

In addition, visual field asymmetries in task performance within the distracter and no distracter condition were also assessed across the unilateral (left versus right) visual field trials, and the bilateral (upper versus lower) visual field trials. The analysis confirmed better performance in the lower visual field relative to the upper visual field in the distracter condition [t(33) = 2.39, p < .05, *d* = .44], and the absence of visual field asymmetries in the no distracter condition (p > .33).

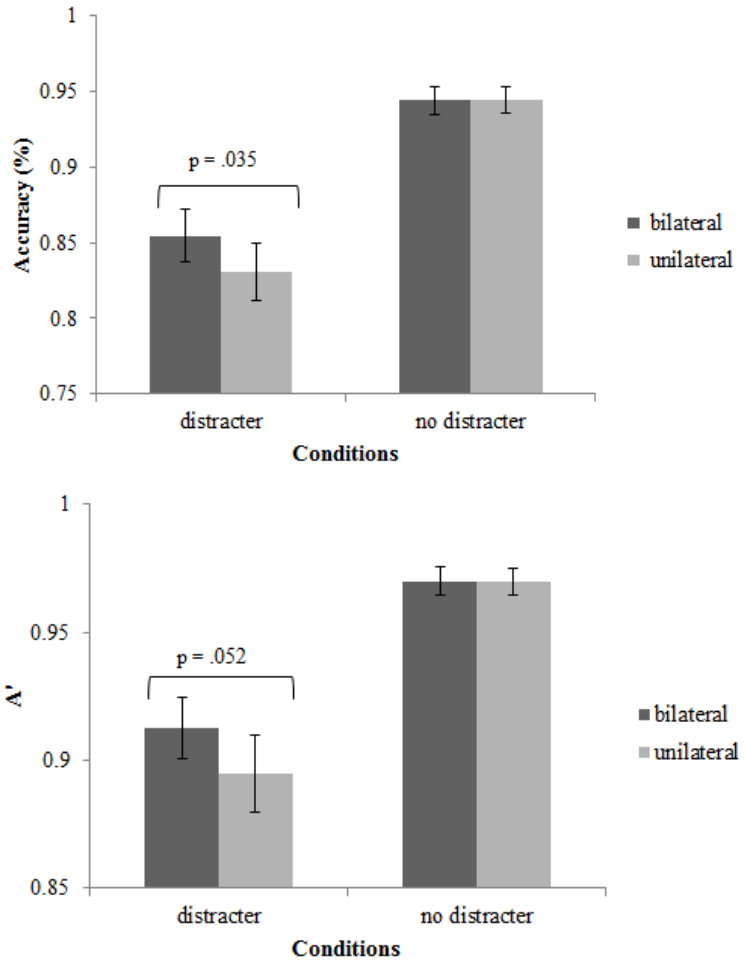

Figure 2.7: The results of Experiment 3. Response accuracy (%) and A´ as a function of condition (distracter, no distracter) and display (bilateral, unilateral). The error bars represent the standard error of the mean values.

2.5.3 Discussion

The aim of Experiment 3 was to address whether the BFA in Experiment 1 can be accounted for by the presentation of spatial pre-cues before the array rather than the filtering of targets from distracters. In addition, the experiment addressed whether the BFA observed in Experiment 1 can be explained by the processing of two target stimuli. Therefore, participants completed a change detection task requiring the selection of targets according to featural cues at encoding. Specifically, participants were required to select targets from distracters on the basis of shape whereby targets were cross-shaped and distracters were circle-shaped. Performance in a size two no distracter condition without those selection

demands was also completed to directly compare performance across distracter and no distracter conditions with the same target set size.

Replicating the findings of Experiment 1, the results revealed a BFA in the distracter condition which required participants to select two targets among distracters. Furthermore, no hemifield effects were observed in the no distracter condition despite also requiring the maintenance of two target stimuli. Therefore, the findings strongly suggest that the BFA in Experiment 1 cannot be simply accounted for by the processing of two target stimuli or by the presentation of pre-cues before the memory array. Instead, the findings strongly support that the BFA is a feature of selecting targets from distracters. In line with Experiment 1, the results suggest that the process of selecting targets from distracters was more efficient within bilateral relative to unilateral displays since the difference in performance between the 2 + 2 distracter condition and the 2 + 0 no distracter condition was reduced within bilateral relative to unilateral displays.

As in Experiment 1, the memory stimuli in bilateral and unilateral displays were aligned horizontally and vertically respectively. Therefore, Experiment 4 was conducted to provide further confirmation that the BFA presented here cannot be explained by stimuli alignment. Once again, performance in the distracter condition was utilised however the stimuli were aligned horizontally or vertically within a single hemifield.

2.6 Experiment 4

2.6.1 Method

2.6.1.1 Participants

The participants from Experiment 3 completed the task. The order of experiments was counterbalanced across participants, with 50% of participants firstly completing Experiment 3.

2.6.1.2 Stimuli and procedure

The 2 + 2 distracter condition of Experiment 3 was again tested in this experiment. However, as in Experiment 2, in order to investigate the extent to which bilateral and unilateral performance can be explained by stimuli alignment (horizontal, vertical), the stimuli appeared within a single hemifield (left, right). This was achieved by moving the centre of the display 7.44° to the left or right of fixation.

Participants completed 10 practice trials followed by a single block of 96 experimental trials in which horizontal and vertical trials were intermixed. Again, participants were instructed to rehearse a series of three digits out loud in order to evoke articulatory suppression.

2.6.2 Results

Trials with response times less than 200ms were removed from the data resulting in the exclusion of 0.1% of trials. As discussed below, the analysis on accuracy and A´ displayed a similar pattern of results and confirmed the absence of an advantage for horizontally aligned displays as shown in Experiment 2.

2.6.2.1 Accuracy

In order to examine the influence of stimuli alignment, response accuracy was analysed in a 2 (hemifield: left, right) x 2 (alignment: horizontal, vertical) repeated measures ANOVA. The results revealed no effects of hemifield ($p = .28$) or

alignment (p = .1), however a significant interaction between those factors was revealed [F(1, 33) = 7.10, p < .02, η_p^2 = .18]. To investigate this interaction, paired sample t-tests compared horizontal and vertical alignment within the left and right hemifields separately. The results revealed no effect of alignment in the left hemifield (p = .66), however there was a significant performance advantage for vertically aligned displays in the right hemifield [t(33) = -2.44, p < .05, *d* = .42] (see Figure 2.8). This result may be explained by reduced accuracy in horizontally aligned conditions within the right hemifield relative to the left hemifield [t(33) = 2.24, p < .05, *d* = .39], since no difference in accuracy was observed in the vertically aligned conditions across hemifields (p = .32).

2.6.2.2 A´

Replicating the accuracy analysis, the results on A´ revealed no main effect of hemifield (p = .11), however a trend towards an effect of alignment was shown [F(1, 33) = 3.59, p = .07, η_p^2 = .08] indicating an overall vertical advantage. In addition the interaction between those factors failed to reach significance [F(1, 33) = 3.07, p = .089, η_p^2 = .09]. Paired sample t-tests confirmed a performance advantage for vertically relative to horizontally aligned displays in the right hemifield [t(33) = -2.10, p < .05, *d* = .38] and no effect of alignment in the left hemifield (p = .57; see Figure 2.8). Again, those results may be accounted for due to lower performance in horizontally aligned conditions within the right hemifield relative to the left hemifield [t(33) = 1.93, p = .062, *d* = .34, *marginally significant*], since no difference in performance was observed in the vertically aligned conditions across hemifields (p = .9).

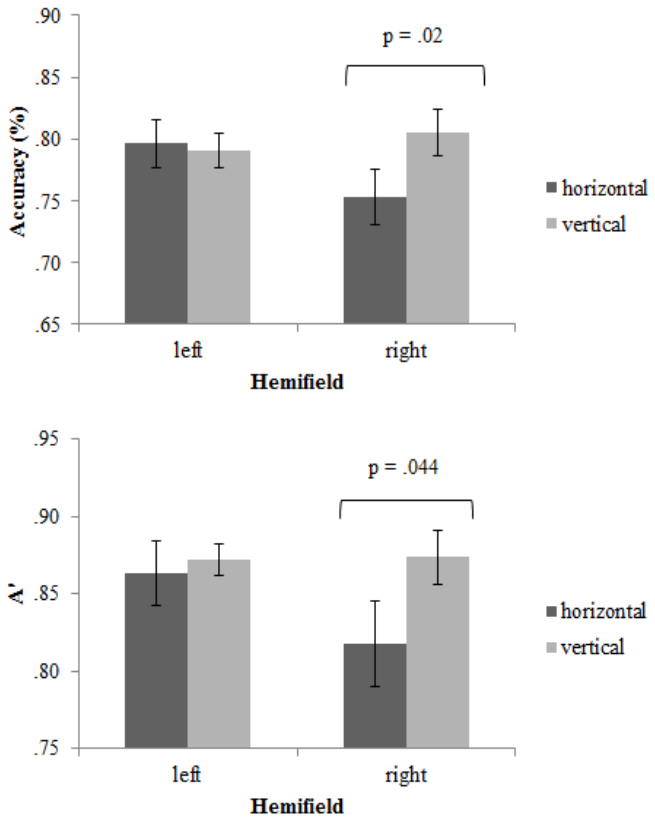

Figure 2.8: The results of Experiment 4. Response accuracy (%) and A´ as a function of hemifield (left, right) and stimuli alignment (horizontal, vertical). The error bars represent the standard error of the mean values.

2.6.3 Discussion

Experiment 4 was conducted to investigate whether the results of Experiment 3 can also be attributed to a performance advantage when processing horizontally aligned displays. Participants completed the distracter condition from Experiment 3, however the stimuli were either horizontally or vertically aligned within one hemifield. Confirming the findings of Experiment 2, the results indicated no evidence of a performance advantage for horizontally aligned displays, suggesting that the BFA cannot be explained by the alignment of the stimuli.

However, unexpectedly, an effect of alignment in the right hemifield was revealed. Nevertheless, this effect was attributable to a performance advantage for vertically aligned displays and thus cannot explain the presence of the BFA in the previous

experiments. Furthermore, the interaction failed to reach significance in the A´ analysis. The inconsistency with the results of Experiment 2 observed here, which also investigated the effect of alignment, may be explained due to a greater tendency for eye-movements across both experiments since the eccentricity of the display was significantly increased (relative to Experiments 1 & 3). In response to this, eye-movements were monitored throughout the remaining experiments in this thesis so that trials could be removed from the analysis when eye-movements occurred.

2.7 General Discussion

2.7.1 Overview of the findings

The aim of Part One was to investigate whether the BFA in colour VSTM is constrained by attentional selective processes. Therefore, colour VSTM was assessed in a change detection paradigm which required participants to select targets from simultaneously displayed distracters on the basis of spatial pre-cues at encoding (Experiment 1). Supporting a role of attentional selection, the BFA emerged in conditions which required selective processing whereas no hemifield effects were observed when participants were required to remember targets in the absence of distracters. Further experiments revealed that the BFA could not be attributed to the horizontal alignment of bilateral presentations (Experiments 2 & 4), and was not solely due to the presence of the spatial pre-cues at encoding (Experiment 3). Specifically, the findings of Experiment 1 were replicated when targets were selected from distracters on the basis of a salient feature (Experiment 3). With previous research revealing a BFA in VSTM for spatial locations (Delvenne, 2005) and orientations (Umemoto et al., 2010) but not for colours (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), it has been suggested that the BFA might be constrained by the nature of the memory

representation (Alvarez & Cavanagh, 2005; Delvenne, 2005). However, the present findings strongly suggest that the BFA is also constrained by the engagement of attentional selective processes.

Previous studies which observed the BFA in non-mnemonic tasks also revealed similar findings, highlighting the emergence of a BFA when required to select and subsequently identify target stimuli among distracters (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). Those findings have recently been replicated in a visual search task which revealed a BFA only when participants were required to select and search a subset of a visual array (Alvarez et al., 2012). Correspondingly, when participants were required to search the whole array, no BFA emerged. In a further experiment, Alvarez and colleagues (2012) showed that the BFA could not be attributed to the difficulty of the task as suggested in earlier studies (e.g. Banich & Belger, 1990; Belger & Banich, 1992). Whilst manipulations to the visual search array increased the difficulty of the task, as indexed through search performance, the BFA failed to emerge. Instead, the BFA only emerged when participants were required to select and search a subset of the visual array.

Likewise, the results of the present experiments suggest that the BFA cannot be explained due to task difficulty. Despite reduced performance in the no distracter conditions of Experiment 1, no hemifield effects were observed. Furthermore, since the no distracter conditions across the experiments assessed performance within two to six item arrays (Experiment 1 & 3), and previous research suggests a VSTM capacity limit of three to four items (Luck & Vogel, 1997; Vogel et al., 2001), the present findings indicate that the BFA cannot be accounted for by differences in over- and under- capacity processing. Instead, the findings strongly suggest that the BFA emerged due to the requirement to select targets from distracters.

In contrast to previous findings (Alvarez et al., 2012), Experiment 3 revealed a BFA when participants were required to select items on the basis of featural information (crossed-shaped targets versus circular-shaped distracters). Despite revealing a BFA in a spatial based selection task, Alvarez and colleagues (2012) found no hemifield effects when participants were required to select targets on the basis of featural information (white targets versus black distracters). Although at first, the results suggest that the effects of selection may be domain specific, on closer inspection it can be identified that differences in the task demands across the experiments may explain this inconsistency.

In Experiment 3, participants were required to select targets from distracters within 100ms and then subsequently remember the target colours throughout a blank retention interval of one second. On the other hand, in Alvarez and colleagues' (2012) feature selection task, the targets and distracters remained visible throughout the trial and could always be distinguished on the basis of colour. Therefore, it may be the case that the observance of the BFA in Experiment 3 can be explained by the greater demand to efficiently select targets from distracters at the encoding stage.

In addition, since the change detection task in Experiment 3 required the maintenance of information across a blank retention interval, it is likely that participants also maintained a representation of the target locations in order to facilitate performance at the test phase. As a result, the BFA may be expected given that previous research has established a BFA in location VSTM (Delvenne, 2005). Correspondingly, in Alvarez and colleagues' (2012) spatial selection task which also revealed a BFA, participants were required to maintain a representation of the selected locations during a retention interval of one second and throughout the search task. Likewise, they suggest that the BFA may be a feature of maintaining spatial selections.

However, since the colours of the memory stimuli could repeat in a given display across both the distracter and no distracter conditions in the present task, the requirement to maintain each target's location was existent across all trials. Therefore, as no hemifield effects were observed in the no distracter conditions, the findings strongly suggest that the initial requirement to select targets from distracters was particularly crucial to the BFA, highlighting the importance of attentional selection at encoding.

2.7.2 Explanations of a BFA in attentional selection

Previous research supports that attentional selection is likely to operate more efficiently across hemifields relative to within hemifields. For instance, studies have highlighted the existence of independent pools of attentional resources within each hemisphere that can function in parallel and improve processing across hemifields (Alvarez & Cavanagh, 2005; Luck et al., 1989, 1994). In addition, further research has demonstrated that attention can be divided to non-contiguous locations more efficiently across hemifields (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007). In response to those studies, Alvarez and colleagues (2012) suggest that the BFA in selection tasks might be explained due to the deployment of multi-focal spatial attention across hemifields (Alvarez et al., 2012). Supporting this possibility, Awh and Pashler (2000) reported a BFA exclusively in tasks which effectively divided the focus of attention to two non-contiguous locations.

Awh and Pashler's (2000) findings suggest that the division of the attentional focus relies on the presence of distracter stimuli in the visual array. However, recent research indicates that the process of splitting spatial attention is not solely stimulus driven. Specifically, Jefferies, Enns and Di Lollo (2014) have recently shown that the division of spatial attention can be flexibly deployed depending on the goals of the observer and their knowledge of the task. In addition, in a review of the divided attention literature, Jans and colleagues (2010) suggest that the division of

resources may also be influenced by the duration of the cue-to-target delay, with long relative to short delays increasing the chance that divided attentional distributions are deployed. Indeed, the observance of the BFA was only shown in the longest cue-to-target delay conditions of Experiment 1.

Reardon and colleagues (2009) suggest that unilateral inferiority in selection tasks can also be accounted for due to an across hemifield advantage in spatially segregating visual information. Drawing upon tasks which have revealed a unilateral field advantage in visual processing (Butcher & Cavanagh, 2008; Pillow & Rubin, 2002), it is evident that those tasks were especially dominated by the ability to perceptually group information. For that reason, Reardon and colleagues (2009) suggest that whilst unilateral superiority might be observed in tasks which require grouping, unilateral inferiority, and thus the BFA, may pertain to tasks which are dominated by the spatial segregation of stimuli.

Furthermore, psychophysical research on selective attentional processing may also provide an understanding of the BFA observed. For instance, Chakravarthi and Cavanagh (2009) highlighted that the within hemifield deficit in selection based studies may be accounted for by the emergence of attentional suppressive surrounds around targets, which although reduce distracter interference, can cause disruption when processing multiple targets. An advantage of across hemifield processing however may be expected since those suppressive regions have been shown to be less effective across the vertical meridian (e.g. Mounts & Gavett, 2004).

Therefore overall, it is evident that a number of studies have demonstrated hemifield effects in attentional processing and can provide plausible explanations of the BFA in perceptually limited selection tasks (Alvarez & Cavanagh, 2012; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). However, in order to draw strong conclusions on the role of attentional selection in promoting

the BFA in VSTM tasks, attentional selection must also influence VSTM processing. Indeed, research suggests this is the case.

2.7.3 The relationship between attentional selection and VSTM

2.7.3.1 Selection during VSTM encoding

2.7.3.1.1 Attentional filtering

A number of electrophysiological studies have shown that the ability to selectively attend to relevant information and subsequently ignore irrelevant information correlates with individual VSTM capacity (Cowan & Morey, 2006; Fukuda & Vogel, 2009; Vogel et al., 2005; Zanto & Gazzaley, 2009). Specifically, those studies revealed that greater VSTM capacity is associated with an increased ability to exclude irrelevant information presented at the encoding stage. In monitoring the neural response to targets and distracters, Zanto and Gazzaley (2009) found that distracter suppression rather than target enhancement correlated with individual VSTM capacity. For that reason, Zanto and Gazzaley (2009) suggest that attending to targets and ignoring distracters are dissociable processes, with the latter process being critical to high performance in VSTM tasks. Indeed, as previously discussed, the present findings suggest that the efficient selection of targets from distracters in the bilateral condition promoted the BFA.

According to Lavie's load theory (Lavie, 1995, 2005), the ability to exclude irrelevant information depends on the perceptual load of the display, which may be determined by factors such as the number or nature of the distracter stimuli. Lavie (1995, 2005) observed that distracters are less likely to be ignored in low relative to high load displays. In order to explain those effects, Lavie (1995, 2005) suggests that the availability of attentional resources may determine whether distracter stimuli are processed. Specifically, in low load conditions, distracters are more likely to be processed since those conditions are less likely to exhaust attentional

resources and thus allow residual resources to be involuntary allocated to the irrelevant stimuli.

Extending this theory, Nishimura, Yoshizaki, Kato and Hatta (2009) revealed that the exclusion of irrelevant information may also be influenced by the hemifield alignment of the display. They showed that distracter stimuli were less likely to be excluded from visual processing in bilateral relative to unilateral displays. As a result, they suggest that those findings may be accounted for due to the existence of separate attentional resource pools within each hemisphere (e.g. Alvarez & Cavanagh, 2005) which increase the availability of attentional resources across the visual field.

However, the results of the present experiments indicate that the selection of targets from distracters was more efficient in bilateral displays. In addition, the results of Experiment 1 revealed that increasing the perceptual load of the display by adding two additional distracter stimuli, did not significantly influence the nature of the BFA. Nevertheless, the findings do not exclude the possibility that further manipulations to the perceptual load within and across hemifields may influence the observance of the BFA in selection tasks.

2.7.3.1.2 Attentional orienting

As well as excluding distracters, recent research suggests that selectively attending to items can also increase the chance that items are stored within VSTM (Botta et al., 2010; Griffin & Nobre, 2003; Makovski & Jiang, 2007; Murray et al., 2011; Schmidt et al., 2002). As previously discussed, those studies revealed that attending to items before encoding, with the use of spatial pre-cues before the array, subsequently improved item recall. Therefore, with more efficient attentional deployment across hemifields (e.g. Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007), it is possible that the requirement to orient attention to the targets at encoding also promoted the BFA in VSTM. This

may be particularly the case in Experiment 1 which used spatial pre-cues before the array. The role of the pre-cues is later addressed in Part Two.

2.7.3.2 Selection during VSTM maintenance

2.7.3.2.1 Attention-based rehearsal

Considering the previous findings, it is likely that the source of the BFA in the present experiments can be located during the encoding stage of the change detection tasks. However, recent research suggests that attentional selection can also be employed beyond the encoding stage, acting as a VSTM rehearsal mechanism (Awh et al., 1998; Williams et al., 2013). As previously discussed, those findings suggest that spatial attention is oriented to the locations previously occupied by memory stimuli in order to support rehearsal in memory. Furthermore, orienting attention within memory to the locations of previously encoded stimuli using retro-cues has also been found to promote VSTM recall, similar to pre-cueing attention at encoding (e.g. Griffin & Nobre, 2003).

Importantly, recent research suggests that retro-cues are more effective when they are distributed across hemifields relative to within a single hemifield (Delvenne & Holt, 2012). As a result, the findings indicate that attentional selection can also operate better across hemifields within VSTM and support a BFA. Given the role of attention within VSTM maintenance (e.g. Awh et al., 1998), it may be hypothesised that bilaterally encoded items may also better survive decay in VSTM relative to unilaterally encoded items. This hypothesis is addressed in Part Two.

2.7.4 Conclusion

In sum, the findings of Part One deliver a new understanding of the BFA in VSTM, providing a direct test of the attentional selection and stimulus domain hypotheses previously proposed (Alvarez & Cavanagh, 2005; Delvenne, 2005). The present findings suggest that the BFA in VSTM is not exclusively constrained by the nature

of the memory representation. Whereas the stimulus domain hypothesis predicted no BFA for colours, the findings revealed a BFA in colour VSTM when required to attentionally select targets from distracters during the encoding stage. Therefore, the findings suggest that the BFA is also constrained by attentional selective processes. Furthermore, the mechanisms of selection and the relationship between attention and VSTM discussed, strongly support the possibility that selective attention can promote the BFA in VSTM.

3 Part Two: The BFA during maintenance in VSTM

3.1 Overview

Given the role of attentional selection in VSTM rehearsal (Awh et al., 1998; Williams et al., 2013), Part Two investigated whether bilaterally encoded items can also better survive decay in VSTM relative to unilaterally encoded items. In order to examine this, participants completed a series of change detection tasks which required items to be maintained in VSTM over two retention intervals (1s, 3s). The results revealed that the BFA increased with time, indicating that bilateral items were resistant to decay since accuracy in bilateral conditions did not decrease across retention intervals (Experiments 5 & 8). On the other hand, VSTM for unilateral items declined as the retention interval increased, suggesting that items were subject to a rehearsal deficit and thus less resistant to decay. However, those effects were only shown when participants were required to attentionally select items at the encoding stage on the basis of spatial pre-cues before the memory array (Experiment 8). Therefore, the results strongly suggest that the way items are encoded into VSTM can impact on the maintenance of those items in the VSTM store. Two possible explanations for the findings are subsequently discussed.

3.2 Introduction

In Part One, the role of attentional selection in the BFA was confirmed, supporting previous claims of the BFA as a signature of attentional selection (Alvarez & Cavanagh, 2005; Alvarez et al., 2012; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009). Since those effects have been shown in a number of non-mnemonic

tasks, it is likely that the source of the BFA can be localised to the encoding stage of the task. However, as briefly outlined in Part One, research suggests that spatial selective attention is also employed beyond the encoding stage and is actively engaged in the rehearsal of information within memory (e.g. Awh et al., 1998). Therefore, it may questioned whether bilaterally encoded objects better survive decay in VSTM relative to unilaterally encoded objects.

Awh and colleagues (1998) provided one of the first compelling demonstrations of spatial selective attention as a rehearsal mechanism in spatial working memory. In a series of spatial location change detection tasks, they aimed to reveal that spatial attention was deployed to the location previously occupied by the memory stimulus. Drawing upon the well documented finding of enhanced visual processing at attended locations (e.g. Posner, 1980), they hypothesised that the ability to detect and discriminate a probe stimulus during the retention interval of a location change detection task, would be improved when presented in a task relevant location. The findings revealed this was the case, revealing faster detection times when the probe was presented in the same location that was previously occupied by the memory stimulus.

Since then, a number of electrophysiological (Awh, Anllo-Vento, & Hillyard, 2000; Jha, 2002) and neuroimaging (Awh et al., 1999; Postle, Jonides, Smith, & D'esposito, 2004) studies have replicated those findings, revealing that stimuli presented in the locations previously occupied by memory stimuli generate a greater cortical response in early visual areas. Jha (2002) showed that this was evident at both the early (400–800ms following memory array offset) and late (2600–3000ms following memory array offset) stages of the retention interval, suggesting that spatial attention is sustained throughout the maintenance period to support rehearsal. Analogous selective attention tasks without mnemonic components have revealed that a similar cortical response is elicited when attending to locations in perception (Awh et al., 2000; Jha, 2002) suggesting that

the same attentional mechanisms may operate during perception and within memory. In addition, Corbetta, Kincade and Shulman (2002) revealed that the same neural circuit is activated when orienting attention in perception and when maintaining items in memory.

In order to provide direct evidence of a role of spatial selective attention during spatial memory rehearsal, Awh and colleagues (1998) also investigated whether disrupting the focus of spatial attention during the retention interval can subsequently reduce spatial memory performance. Their findings revealed this was the case, showing that a colour discrimination task, which required shifts of spatial attention, hindered spatial memory performance when the task was presented during the retention interval. As a result, Awh and colleagues (1998) concluded that the deployment of spatial selective attention at to-be-remembered locations during the retention interval is necessary to rehearse spatial locations in memory.

Since then, similar findings have also been observed in tasks requiring memory for object features (Fougnie & Marois, 2009; Johnson, Hollingworth, & Luck, 2008; Williams et al., 2013). Williams and colleagues (2013) have recently shown that reducing the ability to deploy spatial attention to object locations during VSTM maintenance can attenuate memory for coloured squares, similar to the ones presented in the experiments of Part One. Specifically, they showed that colour memory in a change detection task was reduced when participants were required to monitor and subsequently make a response to a centrally displayed probe stimulus during the retention interval. Furthermore, Williams and colleagues (2013) showed that those effects could not be attributed to general dual-task interference, since an auditory probe interference task, which did not require shifts of visual spatial attention, failed to reduce memory performance to the same extent. In a similar light, previous studies investigating the role of spatial attention in memory for multi-featured objects have also observed that VSTM is reduced, when during the retention interval, tasks which require shifts of spatial attention, such as visual

search (Johnson et al., 2008) and multiple object tracking (Fougnie & Marois, 2009), are performed.

In revealing a role of spatial attention in the rehearsal of object identity information (e.g. object colour), the findings provide a different view of the spatial rehearsal mechanism in relation to what was originally proposed by Awh and colleagues (1998). Specifically, Awh and colleagues (1998) suggested that a rehearsal mechanism relying on spatial selective attention pertains only to spatial memory. Whereas their spatial memory task led to enhanced processing efficiency at the relevant locations during the retention interval, this was not evident when participants were required to remember the identity of the memory stimulus (a letter symbol). In addition, the identity memory task was performed equally well whether or not there was a requirement to shift spatial attention to a new location during the retention interval, unlike the findings of Williams and colleagues (2013).

In order to account for those differences, Williams and colleagues (2013) suggest that the failure to identify a role of spatial attention in object identity rehearsal may be influenced by the number of items that need to be rehearsed. Whereas Awh and colleagues' (1998) study required only one stimulus to be memorised, Williams and colleagues' (2013) task required memory for six items. Supporting this possibility, Williams and colleagues (2013) showed that the extent to which the spatial interference task reduced identity memory was contingent on the number of items presented in the memory array, with conditions requiring memory for three items showing reduced susceptibility to spatial interference. Therefore, Williams and colleagues (2013) suggest that the failure to identify a role of spatial attention in object rehearsal in Awh and colleagues' (1998) study may be explained due to the fact that single item displays place less demand on the spatial rehearsal mechanism. Indeed, it can be expected that change detection tasks with multi-object displays encourage a rehearsal mechanism that is spatial in nature. Specifically, when those tasks require a comparison to be made between the

memory representation held in VSTM and a full probe display at test (as in Williams and colleagues' (2013) experiment) it is plausible that a representation of each object's location is maintained to facilitate performance.

In addition, despite requiring memory for letters, Awh and colleagues (1998) do not report implementing a verbal articulatory suppression task to prevent the rehearsal of the letters through a verbal strategy. On the other hand, the aforementioned studies indicating a role of spatial attention in rehearsal (Fougnie & Marois, 2009; Johnson et al., 2008; Williams et al., 2013), utilise articulatory suppression tasks to avoid this possibility. Therefore, if it is the case that Awh and colleagues (1998) task did not implement this control, it remains possible that the failure to observe a role of spatial attention in rehearsal may also be due to a greater reliance on a verbal relative to visual memory system.

As well as the dual task paradigms discussed, research investigating the impact of attentional selection within VSTM may also support a role of spatial attention in the maintenance of objects in VSTM. As previously outlined, a number of studies have shown that directing attention to the locations of previously encoded objects during the retention interval with the use of retro-cues can improve memory for those objects (e.g. Griffin & Nobre, 2003). In explaining this effect, Kuo, Stokes and Nobre (2012) suggest that attention allows relevant items to be selectively accessed and subsequently biases processing resources in favour of those items. In an electrophysiological study which monitored the number of items in VSTM, they showed that retro-cues led to the withdrawal of processing resources from the irrelevant stimuli, allowing the maintenance of only the cued stimuli.

When utilising two retro-cues, we recently demonstrated that the cue-related advantage in recall is also influenced by the distribution of the cues across the visual field (Delvenne & Holt, 2012). Using a change detection task for coloured squares, we revealed that two retro-cues were more effective when divided

between the two visual hemifields, relative to when both were presented within a single hemifield. Consistent with the findings of Part One, those results support a role of attentional selection in the BFA and indicate that VSTM also benefits from the splitting of attention between the left and right visual fields during maintenance.

As previously mentioned, on the basis of this evidence, it may be questioned whether bilaterally encoded items can better survive decay in VSTM relative to unilaterally encoded items. Given that attentional selection at the encoding stage promotes a BFA (see Part One), and the same attentional mechanisms are likely to be employed to support VSTM maintenance (Awh et al., 1998; Awh et al., 2000; Corbetta et al., 2002; Jha, 2002), then it may be the case that bilateral items are also better maintained in VSTM. As previously discussed, the BFA as a signature of attentional selection may be explained due to the ability to split attention to spatial locations in perception more efficiently across hemifields relative to within a single hemifield (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007). Our recent findings suggest this is also the case within VSTM maintenance (Delvenne & Holt, 2012), revealing that the engagement of attentional selection during VSTM maintenance can also promote a BFA.

Therefore, in order to address whether bilaterally encoded objects are better maintained in VSTM, Experiment 5 assessed VSTM within and across hemifields in a change detection task which manipulated the duration of the retention interval (1s, 3s). As in Part One, participants were required to select targets from distracters on the basis of spatial pre-cues before the memory array. Therefore, a BFA was expected to emerge in colour VSTM since selective processes were predominately engaged.

However, given the role of selection within memory rehearsal, it was predicted that the BFA will also be influenced by the time to maintain the information in memory. Specifically, it was expected that bilaterally encoded items will better survive decay

relative to unilaterally encoded items, resulting in a larger BFA at long (3s) relative to short (1s) retention intervals. Conversely, if bilateral items are no more resistant to decay than unilateral items, the size of the BFA was expected to remain consistent across retention intervals. With the requirement to maintain only the target stimuli amidst distracter stimuli, the task required VSTM for both the colours of the targets and their locations. In relation to the research discussed above, this should maximise the need for a spatial-based rehearsal mechanism during maintenance (Awh et al., 1998; Williams et al., 2013).

3.3 Experiment 5

3.3.1 Method

3.3.1.1 Participants

Fifteen subjects completed the experiment (8 females; mean age = 24 years; range 20-34 years). Participants were neurologically normal with self-reported correct colour vision and normal or corrected-to-normal visual acuity.

3.3.1.2 Stimuli and procedure

A computer-based change detection task, generated using E-Prime computer software (Psychology Software Tools, Inc., www.pstnet.com) was presented on a 17inch screen of a 3.20GHz PC. Participants were seated at a viewing distance of 60cm and a chin-rest was used to reduce movement. All stimuli were presented on a grey screen background (127 of red, blue and green phosphors) which was divided into 4 invisible quadrants (each subtending 4.8° x 4.8°).

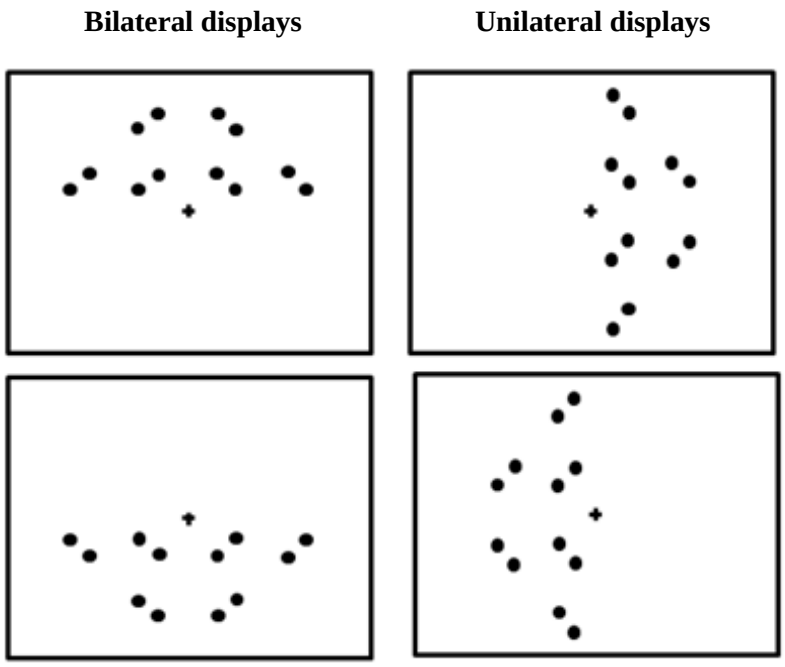

Figure 3.1: An illustration of the fixed positions in the bilateral and unilateral displays of Experiment 5. For clarity, the illustration is not drawn to scale.

On each trial, participants were presented with a black fixation cross (.61° x .61°) at the centre of the screen (500ms) followed by the presentation of 12 white placeholders (.15° x .15°) which were presented at fixed positions across two vertical (unilateral presentation) or two horizontal (bilateral presentation) quadrants indicating the positions of the stimuli to be displayed (500ms). As shown in Figure 3.1, the placeholders within each quadrant were arranged in pairs. The centre-centre distance between each placeholder within a pair was 1.22°. The furthest stimuli from fixation were presented at an eccentricity of 5.76° (centre-centre) and 6.09° to the furthest stimulus edge in the horizontal and vertical directions. The closest stimuli to the vertical and horizontal meridian were presented at a distance of 1.62° centre-centre and 1.29° from each meridian to the nearest stimulus edge.

After 500ms, a placeholder selected at random within each quadrant was enlarged (radius of .34°) cueing the positions of the relevant stimuli to be remembered (50ms). Following a delay of 500ms, 12 coloured squares (.66° x .66°) were

presented at the positions of each placeholder (150ms). Repetition of a colour could not occur within one quadrant however repetition across quadrants was possible. The colour of each square was selected from eight possible colours chosen on the basis of discriminability (red, blue, green, yellow, pink, turquoise, orange, and black). Participants were instructed to remember the colours of the two squares that were cued and to ignore the remaining squares. Following the presentation of the memory array, participants were required to maintain the selected information over a retention interval of either 1 second (50% of trials) or 3 seconds. The placeholders remained present throughout the retention interval.

After the retention interval a whole probe test array was presented. In 50% of the trials a cued stimulus changed colour (target change trials) and in the remaining trials a distracter changed colour (distracter change trials). Only one stimulus within one quadrant could change in a given trial. Since participants were required to detect only target changes, distracter change trials were included to discourage the maintenance of distracter stimuli within the memory array and to therefore increase the demands on attentional selection. In 50% of the distracter change trials, the changed distracter was positioned next to a cued stimulus within the same quadrant (near change) at a centre-centre distance of 1.22°. In the remaining trials, the position of the distracter was restricted to the second closest position within the same quadrant from one of the cued stimuli (far change). Therefore, in distracter change conditions, the distance between the target and the distracter was manipulated within one quadrant of the display. This was manipulated to vary the level of potential distracter interference across trials. The distance of the distracter from the cued stimulus in far change trials was either 2.58°(centre-centre) in the diagonal direction or 3.29° (centre-centre) in horizontal or vertical directions (see Figure 3.2) depending on the position of the cued stimulus. The distance between stimuli across quadrants was always at least 3.24° (centre-centre).

Once the test array was presented, participants were instructed to indicate whether the target colours had changed or stayed the same with a button press (1 = same; 2 = change). They were made aware that in some trials a distracter square could change colour, making it important to precisely select and remember only the target stimuli. Participants were instructed to prioritise accuracy rather than the speed of their response. In addition, throughout the task, participants were required to rehearse three non-consecutive digits on each block of trials in order to evoke articulatory suppression. The digits were rehearsed at a rate of approximately three digits per second.

As outlined above, the experiment had a 2 (change: distracter, target) x 2 (display: bilateral, unilateral) x 2 (retention interval: 1000ms, 3000ms) repeated measures design. Each condition consisted of 32 trials resulting in a total of 256 trials which were randomly distributed in 8 blocks of 32 trials. Participants also completed 16 practice trials before the experimental trials.

3.3.1.2.1 Electrooculography

As previously discussed, eye-movements were monitored throughout all remaining experiments due to the inconsistencies observed in Part 1 which may be attributed to participant eye-movements from central fixation (see Discussion 2.6.3).

Horizontal eye-movements were recorded using Electrooculography (EOG) with BIOPAC systems. Before the experiment, each participant completed a calibration task to gage the voltage of a 1° horizontal eye-movement. This was then used as a criterion to remove subsequent trials where the eyes moved 1° from fixation in the horizontal or diagonal direction (the closest stimulus from fixation was 1.62° (centre-centre) in the horizontal direction). On each trial, eye-movements were monitored from the onset of the placeholders to the offset of the memory array.

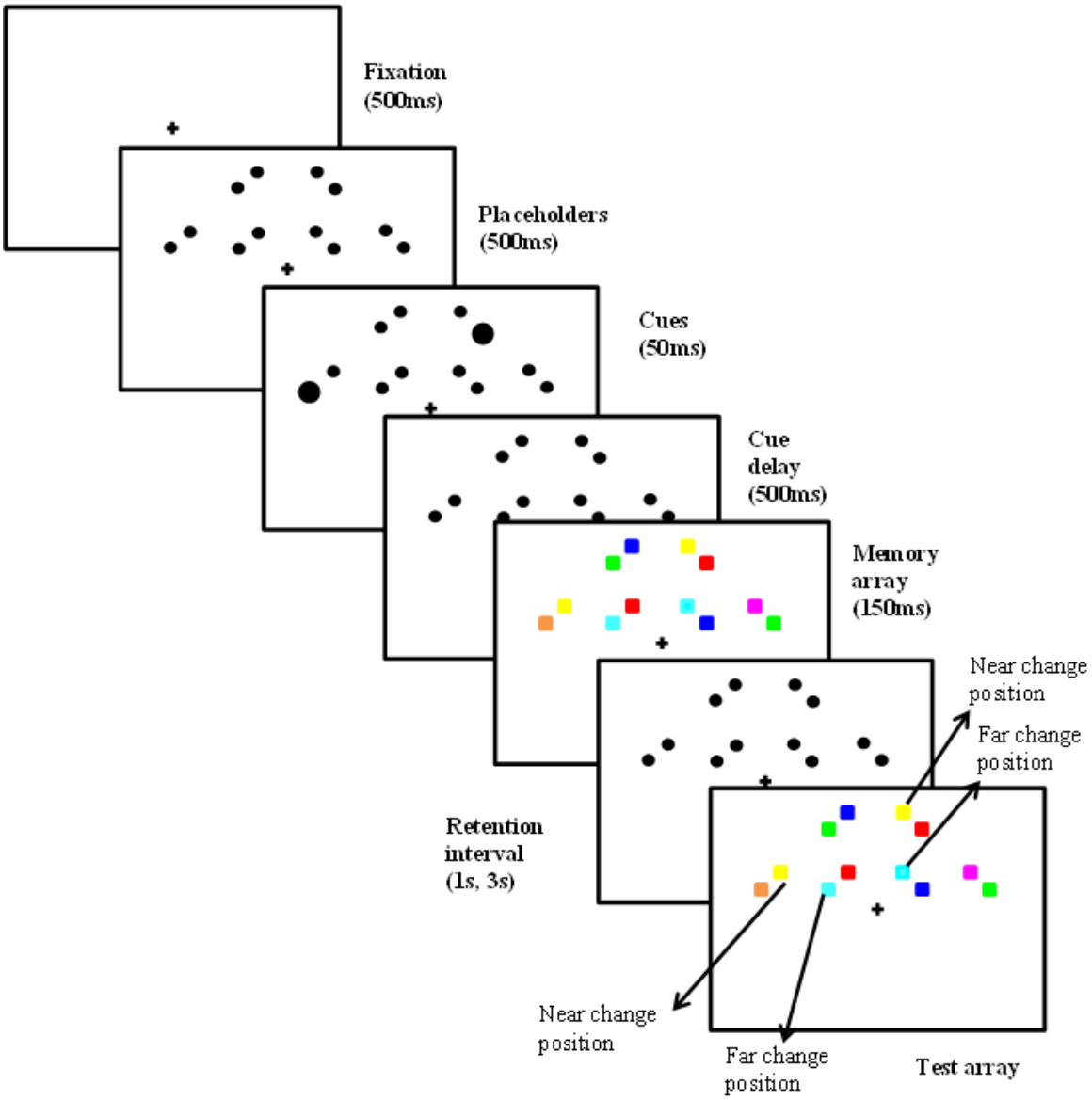

Figure 3.2: The trial procedure of Experiment 5. The arrows in the test array indicate distracters which are located in far and near positions relative to the cued targets within each quadrant. At test, one square changed colour at either of the cued positions or at one of the distracter positions indicated by the arrows. For clarity, the illustration is not drawn to scale.

3.3.2 Results

Horizontal eye-movements greater than 1° constituted 13.97% of trials which were removed from the data. There was no difference in the number of bilateral versus unilateral trials removed [$t(14) = 1.10$, $p = .29$]. In addition, participant trial rejection

rates were within two standard deviations from the mean rejection rate and therefore all participants were included in the following analyses.

As in Part One, mean response accuracy (%) was analysed to assess performance across each condition. However to provide a second representation of the results, A´ was also computed.

3.3.2.1 Accuracy

Mean response accuracy (%) was analysed in a 2 (display: bilateral, unilateral) x 2 (retention interval: 1s, 3s) x 2 (change: target, distracter) repeated measures ANOVA. The results revealed no effect of retention interval (p = .46) or change (p = .31) however a main effect of display was revealed [F(1, 14) = 18.40, p < .002, η_p^2 = .57] which highlighted a significant BFA. Importantly, this effect interacted with retention interval [F(1, 14) = 4.64, p < .05, η_p^2 = .25]. Bilateral-unilateral difference scores were larger at three seconds (8%) relative to one second (3%) [t(14) = -1.96, p = .07, *d* = .51, *marginally significant*] indicating a larger BFA at the longest retention interval. This seems to be accounted for by a decrease in unilateral performance over time [t(14) = 1.79, p = .095, *d* = .51, *marginally significant*] since accuracy in bilateral trials did not differ across retention intervals (p = .44) (see Figure 3.3). No other interactions were revealed (p > .13).

As in Part One, visual field asymmetries were investigated by comparing performance in the bilateral upper and lower visual fields and the unilateral left and right visual fields. Although paired sample t-tests showed no difference in unilateral performance between the left and right hemifields (p = .84), the results revealed better performance in bilateral trials within the lower visual field relative to the upper visual field [t(14) = 4.30, p < .002, *d* = 1.2] . As previously discussed, those effects may be accounted for due to increased spatial resolution in the lower relative to the upper visual field (He et al.,1996; Intriligator & Cavanagh, 2001).

3.3.2.1.1 Distracter interference

Within the distracter change trials, 50% of distracter changes were positioned near to the target whereas in the remaining trials, distracter changes were positioned far from the target. As a result, it might be expected that near change trials produce a greater level of interference on change detection performance relative to far change trials. If the BFA is a signature of selecting targets from distracters, a larger BFA may also be expected in near change trials, given that the demands on efficient selection are increased at the test phase. In order to investigate whether the BFA was influenced by this factor, accuracy was analysed in a 2 (distracter distance: near, far) x 2 (display: bilateral, unilateral) x 2 (retention: 1s, 3s) repeated measures ANOVA. Although the results revealed significant effects of distracter distance [$F(1, 14) = 7.26$, $p < .02$, $\eta_p^2 = .34$] and display [$F(1, 14) = 14$, $p < .005$, $\eta_p^2 = .5$], no interactions with distracter distance were observed ($p > .32$). Specifically, the analysis revealed a BFA across all trials despite revealing better performance in far change trials relative to near change trials. Therefore, the results revealed no effect of distracter distance on the BFA. Further analysis confirmed visual field asymmetries in performance with greater accuracy in bilateral trials within the lower visual field relative to the upper visual field [$t(14) = 4.74$, $p < .001$, $d = 1.39$] and no difference in unilateral performance between the left and right visual fields ($p = .86$).

3.3.2.2 A´

A two-way 2 (display: bilateral, unilateral) x 2 (retention: 1s, 3s) repeated measures ANOVA was conducted on A´. The results confirmed the accuracy analyses revealing no effect of retention interval ($p = .54$) and a main effect of display [$F(1, 14) = 10.08$, $p < .01$, $\eta_p^2 = .42$] which indicated a significant BFA. The effect of display also significantly interacted with retention interval [$F(1, 14) = 5.72$, $p < .05$, $\eta_p^2 = .29$]. Paired sample t-tests on bilateral-unilateral difference scores revealed a significantly larger BFA at three seconds (8%) relative to one second (2%) [$t(14) =$ -

2.39, p < .05, *d* = .66]. In addition, performance in unilateral conditions decreased as the retention interval increased [t(14) = 1.81, p = .092, *d* = .51, *marginally significant*] however no difference in accuracy was shown in the bilateral condition (p =.32). The visual field asymmetry analysis confirmed no difference between unilateral performance in the left and right hemifields (p = .95) whereas better performance was showed in the bilateral lower visual field relative to the upper visual field [t(14) = 3.57, p < .005, *d* = 1.09].

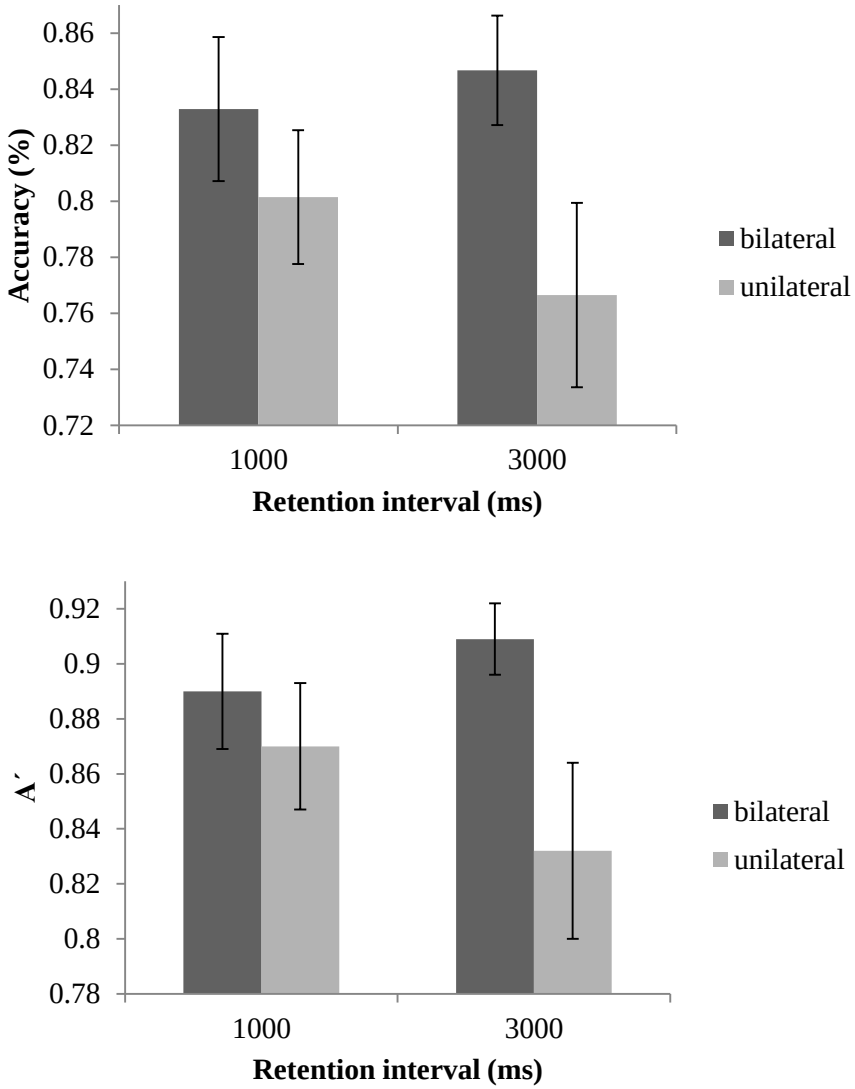

Figure 3.3: Results of Experiment 5. Mean response accuracy (%) and A´ as a function of retention interval (1000ms, 3000ms) and display (bilateral, unilateral). Error bars represent the standard error of the mean values.

3.3.3 Discussion

The aim of Experiment 5 was to investigate whether bilaterally encoded items better survive decay in VSTM relative to unilaterally encoded items. Replicating the results of Part One, a BFA was observed in colour VSTM when during the encoding stage, participants were required to select targets from distracters. However, extending those results, the findings revealed that the BFA increased as the duration of the retention interval increased (1s, 3s). A closer look at the results revealed that performance in the bilateral conditions remained consistent over time whereas performance in the unilateral conditions declined. Therefore, the findings strongly suggest that bilateral items can better survive decay in VSTM.

Despite reduced performance when distracters near to the target changed at test, suggesting a greater level of interference, this did not influence the nature of the BFA. Therefore, those findings may suggest that the BFA was elicited due to the initial selection requirement at the encoding stage rather than due to the demands of the test phase. However, this finding should be treated with caution due to the limited range of distracter distances utilised. A replication of the results across a greater range of distracter distances is required to establish firm conclusions.

As previously outlined, bilateral items may survive decay in VSTM since VSTM rehearsal relies on spatial based selection during maintenance (Awh et al., 1998; Williams et al., 2013). Indeed, the findings of Part One suggest that tasks which engage spatial based selection can promote a BFA in VSTM. Those effects may be explained since spatial attention can be split more effectively to locations across hemifields relative to within a hemifield (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007).

However, since Experiment 5 predominately engaged spatial selective attention at the beginning of each trial, by requiring participants to selectively process targets amidst distracters, it may be questioned to what extent the nature of the BFA within

VSTM maintenance can be explained by this requirement. Since it has been found that spatial selection in perception and during VSTM maintenance rely on the same attentional mechanisms (Awh et al., 2000; Corbetta et al., 2002; Jha, 2002), it may be the case that the demands on selection at the encoding stage, which facilitated the splitting and orienting of spatial attention to the relevant locations, was also maintained during VSTM maintenance, promoting a BFA during rehearsal.

Nevertheless, it can be expected that the selection demand at the encoding stage may not be crucial to observe a BFA during maintenance. For instance, Umemoto and colleagues' (2010) findings suggest that the BFA can emerge within VSTM maintenance in the absence of encoding differences within and between hemifields. In addition, our recent findings suggest that attention can also be split during memory maintenance and promote a BFA in the absence of selective pre-cues at the encoding stage (Delvenne & Holt, 2012). Therefore, the following experiments addressed whether the nature of the BFA within VSTM maintenance can be observed in the absence of those selection requirements at encoding. As participants were required to remember both the locations of the targets and their colours, Experiments 6 & 7 investigated the maintenance of each of those stimulus domains respectively. Indeed, research suggests a role of spatial attention in the rehearsal of both object (Williams et al., 2013) and location information (Awh et al., 1998) in VSTM.

Although the findings so far have confirmed the absence of a BFA for colour VSTM, as shown consistently in previous studies (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), research has not yet examined whether hemifield effects may emerge in colour VSTM beyond retention intervals of one second. It may be the case that a BFA emerges at longer retention intervals since the demands on VSTM rehearsal are increased. With recent evidence revealing that the rehearsal of colour specifically relies on spatial selective attention (Williams et al., 2013) which as discussed, can be deployed more effectively across hemifields (e.g. Awh & Pashler,

2000), it may be the case that bilateral attentional resources maintain colours more effectively over longer intervals relative to unilateral resources.

However, as previously discussed, unlike colour VSTM tasks, research has revealed that a BFA can be found in location VSTM tasks with retention intervals of one second (Delvenne, 2005). According to this rehearsal demand hypothesis, the observance of a BFA suggests that maintaining locations in VSTM places a greater demand on the spatial based rehearsal mechanism relative to colours. Supporting this possibility, a number of studies have shown that spatial memory is intrinsically related to spatial attention (Awh & Jonides, 2001) and suggest that spatial relative to identity VSTM relies on spatial based rehearsal mechanisms to a greater extent (Awh et al., 1998). Nevertheless, in the same way, it may be expected that the BFA in location VSTM will become larger as the retention interval is increased, since longer retention intervals place further demands on efficient VSTM rehearsal.

3.4 Experiments 6 & 7

3.4.1 Experiment 6

3.4.2 Method

3.4.2.1 Participants

Thirteen subjects completed the experiment (10 females; mean age = 25 years; range 19-32 years). Participants were neurologically normal with self-reported correct colour vision and normal or corrected-to-normal visual acuity.

3.4.2.2 Stimuli and procedure

The methodology was the same as in Experiment 5 with the exception that the spatial pre-cues and distracter stimuli were not presented (see Figure 3.4). Therefore, participants were required to remember two colours on each trial. In order to reduce the chance of ceiling effects, colour contrast was added as an

additional variable. In 50% of the trials, colours were selected from the eight high contrast colours presented in Experiment 5. In the remaining trials, low contrast colours were selected from six possible shades of red which were created by manipulating the saturation (S) and luminance (L) values in the following way: (1) L= 100%, S = 100%; (2) L=66%, S=66%; (3) L=33%, S=66%; (4) L=33%, S=100%; (5) L=66%, S=100%; (6) L=100%, S=33%. As only two colours were presented on each trial, colours were not repeated within the memory array and a new colour was presented at test on change trials.

Experiment 6 therefore had a 2 (colour contrast: high, low) x 2 (display: bilateral, unilateral) x 2 (retention interval: 1s, 3s) repeated measures design with 32 trials in each condition. Altogether participants completed 256 experimental trials, which were randomly blocked into 8 blocks of 32 trials, and 16 practice trials. As in Experiment 5, participants completed an articulatory suppression task on each block of trials which required the rehearsal of three digits at a rate of approximately three digits per second. In addition, as outlined in Experiment 5, eye-movements were monitored using EOG.

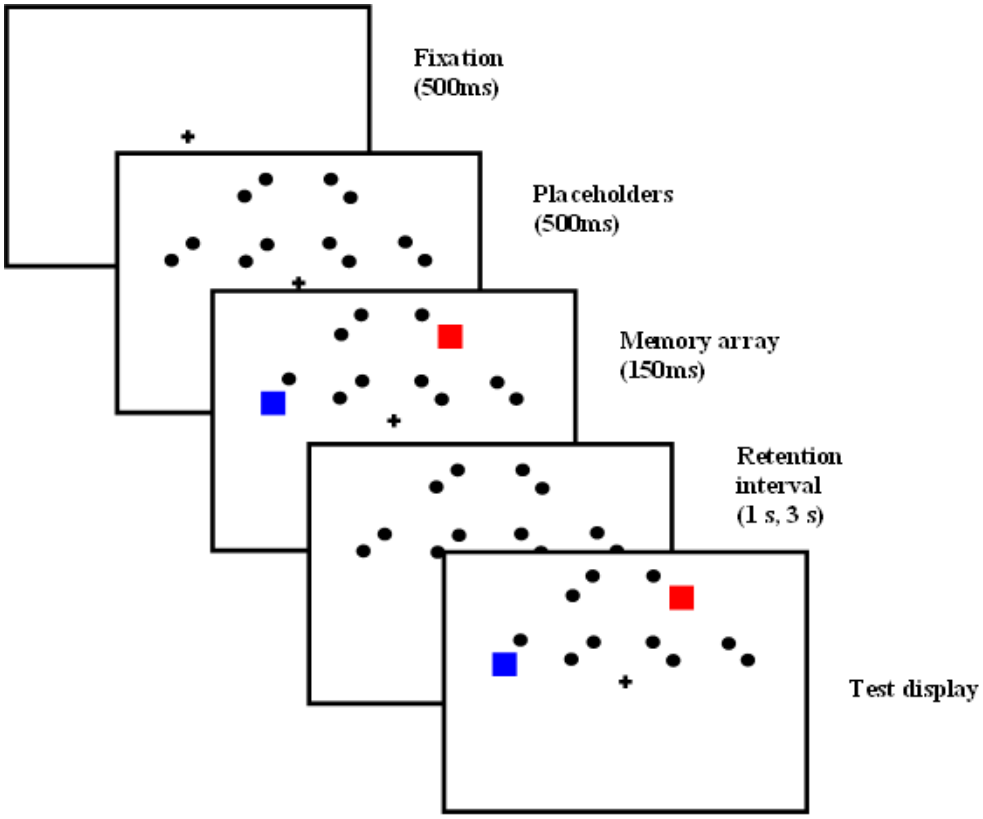

Figure 3.4: The trial procedure of Experiment 6. For clarity, the illustration is not drawn to scale.

3.4.3 Results

Horizontal eye-movements greater than 1° constituted 12.89% of trials which were subsequently removed from the data. The number of trials removed across each display condition (bilateral, unilateral) [t(12) = -.88, p = .40] and each colour contrast condition (high, low) [t(12) = .40, p = .69] did not differ. In addition, each participant's trial rejection rate was within two standard deviations from the mean rejection rate and therefore all participants were included in the following analyses. As in the previous experiments, performance across each condition was analysed as a function of mean response accuracy (%) and A´.

3.4.3.1 Accuracy

Mean response accuracy (%) was assessed in a 2 (colour contrast: low, high) x 2 (display: bilateral, unilateral) x 2 (retention interval: 1s, 3s) repeated measures

ANOVA. The results revealed an effect of colour contrast [F(1, 12) = 89.72, p < .001, η_p^2 = .88] with greater accuracy in high relative to low contrast conditions, and a main effect of retention interval [F(1, 12) = 10.31, p < .01, η_p^2 = .46], revealing greater accuracy at one second relative to three seconds. However, no other main effects or interactions were shown (p > .22) (see Figure 3.5). In addition, paired sample t-tests revealed no visual field asymmetries within bilateral (up, down) or unilateral (left, right) displays (p > .14).

3.4.3.2 A´

The following analysis on A´ replicated the accuracy analysis above revealing a main effect of colour contrast [F(1, 12) = 81.73, p < .001, η_p^2 = .87] and retention interval [F(1, 12) = 11.74, p < .01, η_p^2 = .5]. A trend towards an interaction between colour and retention interval [F(1, 12) = 4.2, p = .068, η_p^2 = .26] was shown, indicating that low contrast colours decayed to a greater extent across retention intervals relative to high contrast colours. However, subsequent paired sample t-tests suggest this difference was not significant (p > .12). No other main effects or interactions were identified (p > .44). In addition, paired sample t-tests within bilateral (up, down) and unilateral (left, right) displays revealed no evidence of visual field asymmetries in performance (p > .12).

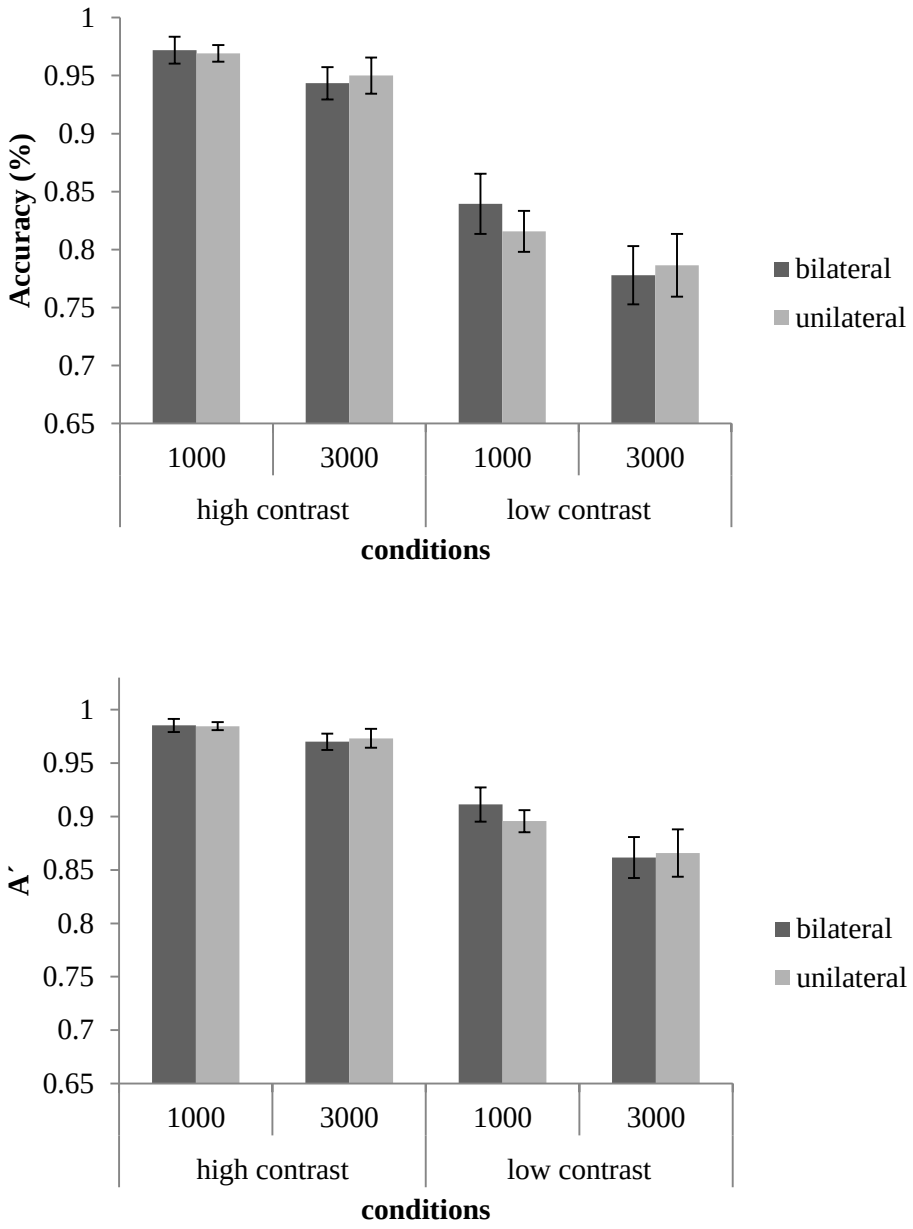

Figure 3.5: Results of Experiment 6. Mean response accuracy (%) and A´ as a function of colour contrast (high, low), retention (1000ms, 3000ms) and display (bilateral, unilateral). Error bars represent the standard error of the mean values.

3.4.4 Experiment 7

3.4.5 Method

3.4.5.1 Participants

Fifteen subjects completed the experiment (13 females; mean age = 19.33 years; range 18-21 years). Participants were neurologically normal with self-reported correct colour vision and normal or corrected-to-normal visual acuity.

3.4.5.2 Stimuli and procedure

The methodology was the same as in Experiment 6, however participants were instructed to remember the locations of the squares presented in the memory array. In order to avoid the rehearsal of colour, the squares remained black throughout the trials. In addition, at test, a single probe was used to discourage participants from memorising the spatial configurations of the memory stimuli (see Figure 3.6). In 50% of the trials, one stimulus moved to a new location which appeared equally within each quadrant, whereas in the remaining trials, the locations of the stimuli did not change. The size of the location change was also manipulated using the same near and far change criteria as in Experiment 5. Therefore, at test, the changed location was either near to (50% of trials) or far from the original location in the memory array.

Consequently, Experiment 7 had a 2 (change: change, no change) x 2 (display: bilateral, unilateral) x 2 (retention interval: 1, 3) repeated measures design with 32 trials in each condition. Altogether, participants completed 256 experimental trials, which were randomly distributed into 8 blocks of 32 trials, and 16 practice trials. In addition, participants completed an articulatory suppression task on each block of trials which required the rehearsal of three digits at a rate of approximately three digits per second. Also, as outlined in Experiment 5, eye-movements were monitored using EOG.

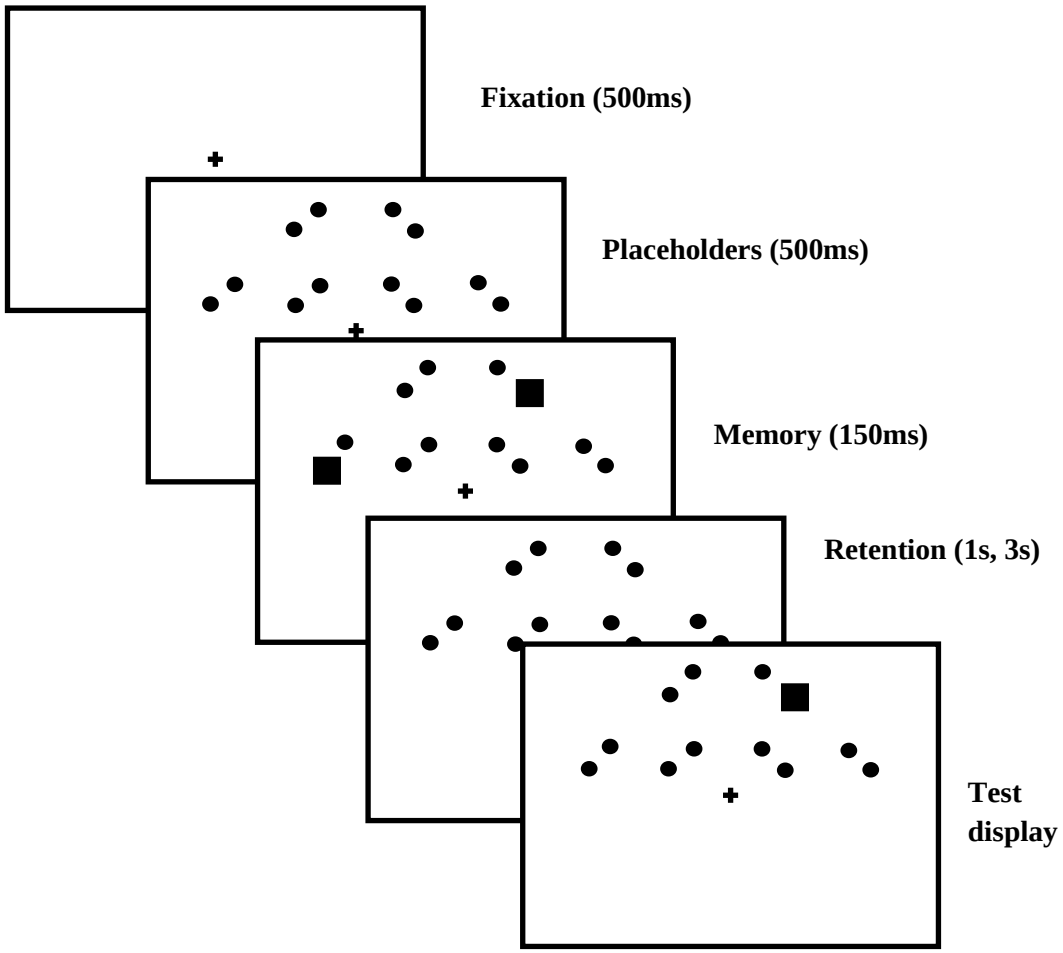

Figure 3.6: The trial procedure of Experiment 7. For clarity, the illustration is not drawn to scale.

3.4.6 Results

Horizontal eye-movements greater than 1° constituted 14.11% of trials and were removed from the data. No difference was shown in the number of bilateral versus unilateral trials removed [$t(14) = .61$, $p = .55$], and participant trial rejection rates were within two standard deviations from the mean rejection rate. As in the previous experiments, performance across each condition was analysed as a function of mean response accuracy (%) and A´.

3.4.6.1 Accuracy

Mean response accuracy (%) was analysed in a 2 (display: bilateral, unilateral) x 2 (retention interval: 1s, 3s) repeated measures ANOVA. The results revealed an effect of retention interval [$F(1, 14) = 5.09$, $p < .05$, $\eta_p^2 = .27$] showing greater accuracy at one second relative to three seconds. In addition, a main effect of display was shown [$F(1, 14) = 17.13$, $p < .002$, $\eta_p^2 = .55$] highlighting a significant BFA. However, no interaction between retention and display was revealed ($p = .65$; see Figure 3.7). Paired sample t-tests also revealed no visual field asymmetries in accuracy across bilateral (up, down) or unilateral (left, right) displays ($p > .32$).

3.4.6.1.1 Location change distance

Further analysis investigated whether the distance of the location change at test (near, far) relative to the position of the relevant location in the memory array influenced the observance of the BFA. Although a 2 (distance: near, far) x 2 (display: bilateral, unilateral) x 2 (retention: 1s, 3s) repeated measures ANOVA revealed an effect of distance [$F(1, 14) = 28.59$, $p < .001$, $\eta_p^2 = .67$], indicating better performance in far change trials relative to near change trials, no interactions with distance were revealed ($p > .27$). Therefore, the analysis indicates that the BFA in the present task cannot be explained by the level of spatial precision required to detect location changes.

3.4.6.2 A´

The analysis on A´ replicated the accuracy analyses showing a main effect of retention interval [$F(1, 14) = 3.72$, $p = .074$, $\eta_p^2 = .21$, *marginally significant*] with greater accuracy at one second relative to three seconds. In addition a main effect of display was revealed [$F(1, 14) = 10.31$, $p < .01$, $\eta_p^2 = .42$], highlighting a significant BFA. However no interaction between retention and display was shown

(p = .83). Paired sample t-tests also revealed no visual field asymmetries in accuracy across bilateral (up, down) or unilateral (left, right) displays (p > .4).

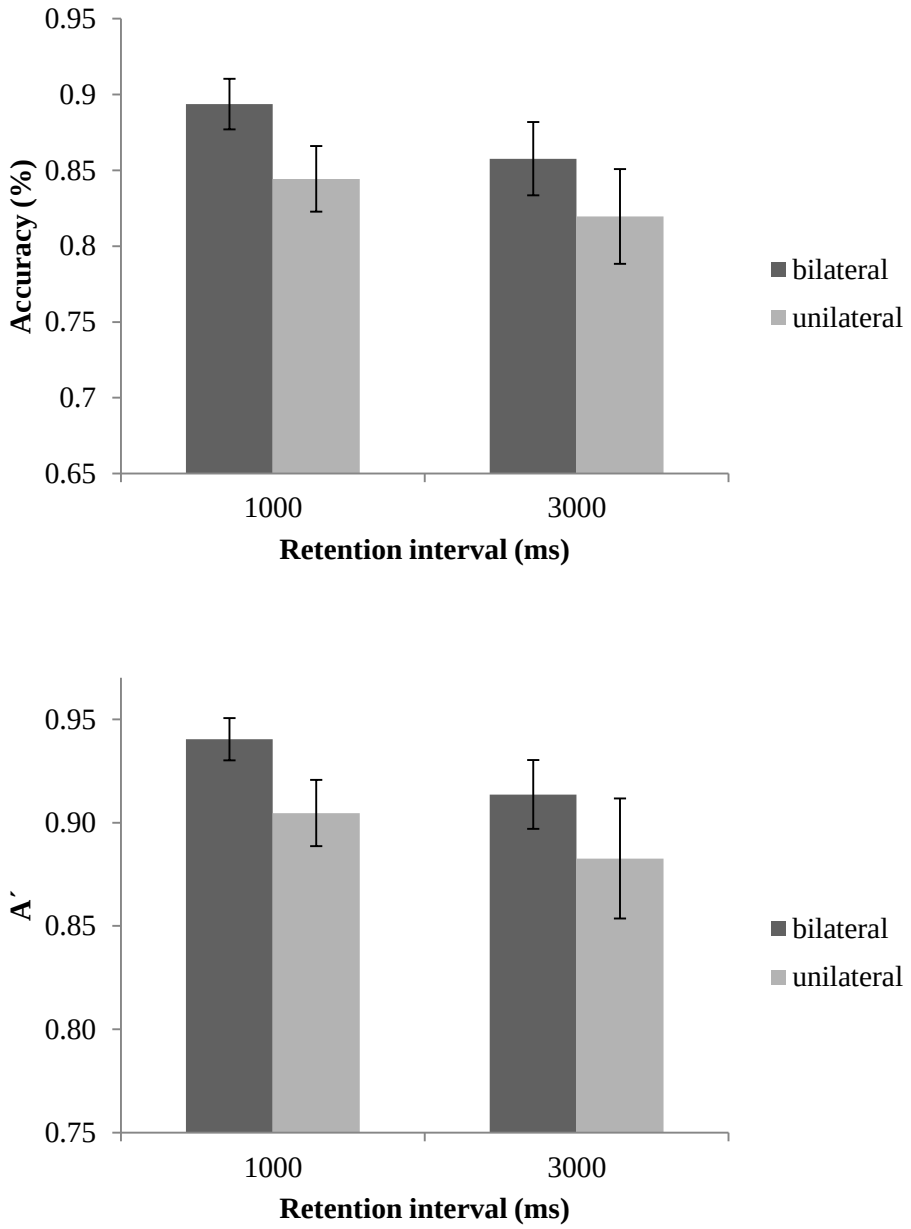

Figure 3.7: Results of Experiment 7. Mean response accuracy (%) and A´ as a function of retention interval (1000ms, 3000ms) and display (bilateral, unilateral). Error bars represent the standard error of the mean values.

3.4.7 Discussion

The aim of Experiments 6 and 7 was to assess whether the findings of Experiment 5, which revealed better maintenance of bilaterally encoded relative to unilaterally encoded stimuli over time, can be replicated in the absence of the selection requirements at the encoding stage. Since Experiment 5 required participants to memorise both the colours and the locations of the target stimuli, the experiments addressed whether the findings can be explained by the maintenance of either of those stimulus domains. As previously discussed, research investigating the maintenance of information in memory has identified a role of spatial selective attention in the rehearsal of both stimulus domains (Awh et al., 1998; Williams et al., 2013) and thus a BFA may be expected during VSTM maintenance. However, both experiments revealed no evidence of an interaction between hemifield effects and the retention interval, suggesting that the results of Experiment 5 are unlikely to be attributed to VSTM for colours (Experiment 6) or locations (Experiment 7) alone. Instead, the findings suggest that those effects were dependent on the selection requirements at encoding.

In Experiment 6, VSTM for both high and low contrast colours was assessed in order to reduce the possibility of ceiling effects. However, despite observing a reduction in VSTM performance over time, the findings showed no hemifield effects. As a result, Experiment 6 provides further confirmation of the absence of a BFA for colour VSTM (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012) suggesting that neither the duration of the retention interval or the resolution of the encoded colours, can explain those findings.

Whereas the findings of Experiment 7 did reveal a BFA in a location VSTM task, replicating previous research (Delvenne, 2005), the results revealed that the BFA was not influenced by the duration of the retention interval. Instead, the size of the BFA remained consistent over time due to a reduction in both unilateral and

bilateral performance as the retention interval increased. Therefore, the findings suggest that the nature of the BFA during VSTM maintenance in Experiment 5 is not simply a feature of maintaining object locations over longer durations.

However, in Experiment 5, participants were in fact required to remember simultaneously both the colour and location of the target stimuli thus necessitating the ability to bind those representations together. For that reason, it may be questioned whether the maintenance of those bindings can explain the BFA during maintenance. However, suggesting this is unlikely to be the case, a number of studies have shown that bound VSTM representations do not require additional attentional support during rehearsal relative to single feature memory (Delvenne et al., 2010; Gajewski & Brockmole, 2006; Johnson et al., 2008; Yeh, Yang, & Chiu, 2005; but see Fougnie & Marois, 2009). In addition, as previously discussed, the requirement to maintain object-location bindings was also present in the previously reported colour VSTM tasks with no distracters (see Experiment 1), however those conditions did not promote a BFA.

As a result, the findings above suggest that the nature of the BFA within VSTM maintenance was influenced by the task demands on selection at the encoding stage. As previously discussed, if VSTM maintenance is achieved through the orienting of spatial attention to target locations (Awh et al., 1998; Williams et al., 2013), it is plausible that orienting attention to target locations at the encoding stage may facilitate this process. For that reason, Experiment 8 investigated whether simply orienting attention to the locations of the stimuli with the use of pre-cues can also produce a BFA within VSTM and replicate the findings of Experiment 5. As a result, participants were no longer required to filter targets from distracters but were simply instructed to remember two target colours which were preceded by spatial pre-cues.

3.5 Experiment 8

3.5.1 Method

3.5.1.1 Participants

Sixteen subjects completed the experiment (11 females; mean age = 22.13 years; range = 19-32 years). Participants were neurologically normal with self-reported correct colour vision and normal or corrected-to-normal visual acuity.

3.5.1.2 Stimuli and procedure

The trial procedure was the same as in Experiment 6 which investigated memory for two colours, however the memory array was preceded by the presentation of two spatial pre-cues (50ms) with a cue-to-target delay of 500ms (see Figure 3.8). To avoid possible ceiling effects, only low contrast colours were used in the memory array. Therefore, the experiment had a 2 (display: bilateral, unilateral) x 2 (retention: 1s, 3s) repeated measures design with 32 trials in each condition. In total, participants completed 128 trials, which were randomly distributed into 4 blocks, and 16 practice trials. In addition, participants completed an articulatory suppression task on each block of trials which required the rehearsal of three digits at a rate of approximately three digits per second. In addition, as outlined in Experiment 5, eye-movements were monitored using EOG.

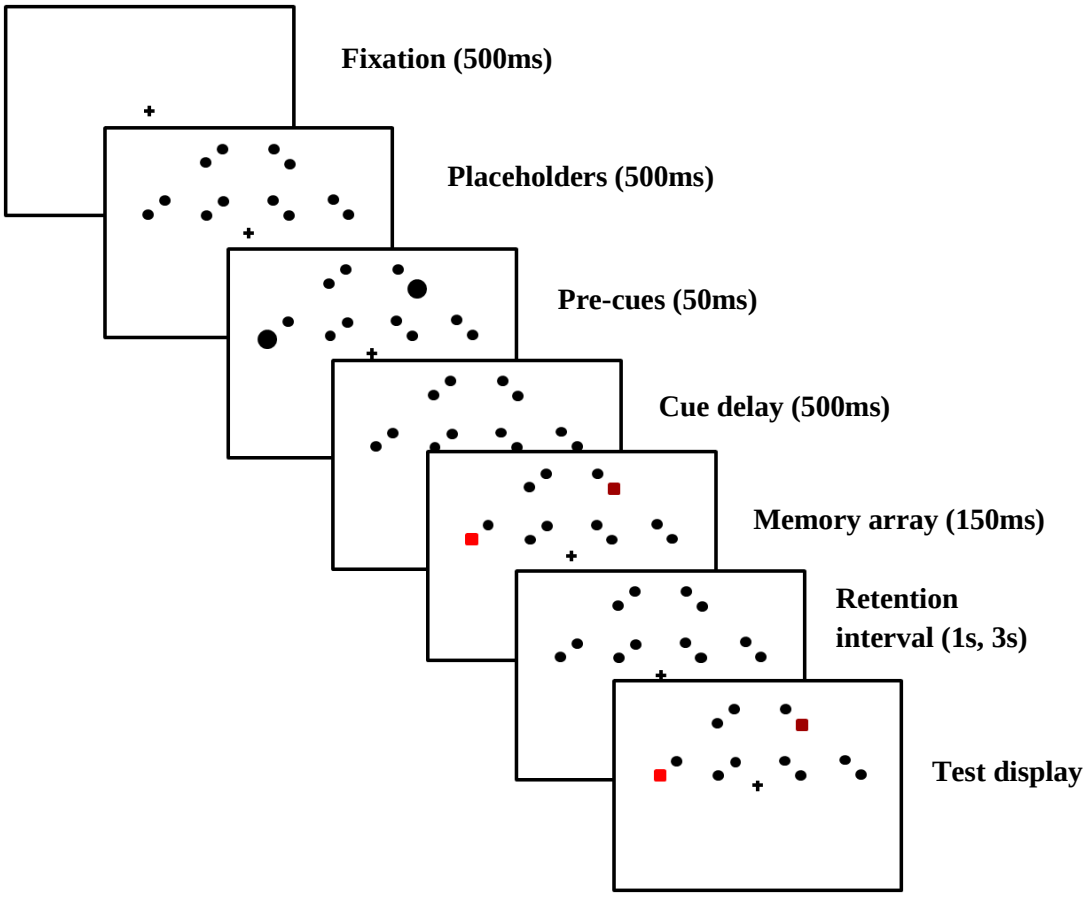

Figure 3.8: The trial procedure of Experiment 8. For clarity, the illustration is not drawn to scale.

3.5.2 Results

Horizontal eye-movements greater than 1° constituted 13.77% of trials and were removed from the data. No difference was shown in the number of bilateral versus unilateral trials removed [t(15) = 0, p = 1] and participant trial rejection rates were within two standard deviations from the mean rejection rate. As in the previous experiments, performance across each condition was analysed as a function of mean response accuracy (%) and A´.

3.5.2.1 Accuracy

Mean response accuracy (%) was analysed in a 2 (display: bilateral, unilateral) x 2 (retention interval: 1s, 3s) repeated measures ANOVA. The results revealed an

effect of retention interval [F(1, 15) = 14.51, p < .005, η_p^2 = .49] showing greater accuracy at one second relative to three seconds and a main effect of display was shown [F(1, 15) = 6.47, p < .05, η_p^2 = .30] highlighting a significant BFA. Importantly, a significant interaction between retention and display [F(1, 15) = 6.19, p < .05, η_p^2 = .29] was revealed. Paired sample t-tests showed a BFA at three seconds only [t(15) = 4.37, p < .002, *d* = 1.09], however no hemifield effects were shown at one second (p = .59). In addition, paired sample t-tests showed that only unilateral performance declined as the retention interval increased [t(15) = 4.18, p < .002, *d* = 1.04], with no difference in bilateral performance over time (p= .31; see Figure 3.9). Further analysis indicated the absence of visual field asymmetries in performance within bilateral (up, down) and unilateral (left, right) displays (p > .18).

Since no hemifield effects were shown in Experiment 6 which required memory for two colours in the absence of the spatial pre-cues, the results strongly suggest that orienting attention to the locations of the colours before presentation influenced the observance of the BFA. In order to confirm this suggestion, Experiments 6 and 8 were included in a three-way 2 (retention: 1s, 3s) x 2 (display: bilateral, unilateral) x 2 (cue: cue, no cue) mixed ANOVA with cue (cue, no cue) as a between subjects variable. In Experiment 6, only the conditions which required memory for low contrast colours were included in the analysis to match Experiment 8 more closely. The results revealed a main effect of retention interval [F(1, 27) = 20, p < .001, η_p^2 = .43], due to a reduction in accuracy in conditions with a retention interval of three seconds relative to one second. Importantly, a significant interaction between cue, retention and display [F(1, 27) = 5.41, p < .05, η_p^2 = .17] was also revealed. With reference to the results above and to those of Experiment 6, the interaction further indicates no hemifield effects in the absence of spatial pre-cues but a significant BFA at three seconds when spatial pre-cues preceded the memory array. No other main effects or interactions were shown (p > .12).

3.5.2.2 A´

The analysis on A´ replicated the accuracy analyses above showing an effect of retention interval [F(1, 15) = 15.88, p < .002, η_p^2 = .51], with better performance in retention interval conditions of one second relative to three seconds, and a significant effect of display [F(1, 15) = 8.19, p < .05, η_p^2 = .35], revealing a BFA. In addition, the interaction between retention and display was significant [F(1, 15) = 6.04, p < .05, η_p^2 = .29], indicating a BFA in conditions with a retention interval of three seconds [t(15) = 3.53, p < .005, *d* = .91] and no hemifield effects at one second (p = .74). Paired sample t-tests also revealed a decline in unilateral performance as the retention interval increased [t(15) = 3.97, p < .002, *d* = 1.01] whereas bilateral performance remained consistent over time (p =.16). As reported above, no visual field asymmetries in performance across bilateral (up, down) or unilateral (left, right) displays were shown (p > .2).

The A´ scores were also compared with those of Experiment 6 in a three-way 2 (retention: 1s, 3s) x 2 (display: bilateral, unilateral) x 2 (cue: cue, no cue) mixed ANOVA, with cue (cue, no cue) as a between subjects variable. Again, only the low contrast colour conditions from Experiment 6 were included. The results replicated the accuracy analysis above, revealing a main effect of retention interval [F(1, 27) = 24.11, p < .001, η_p^2 = .47] and an interaction between cue, retention and display [F(1, 27) = 4.18, p = .051, η_p^2 = .13, *marginally significant*]. No other main effects or interactions were revealed (p > .1).

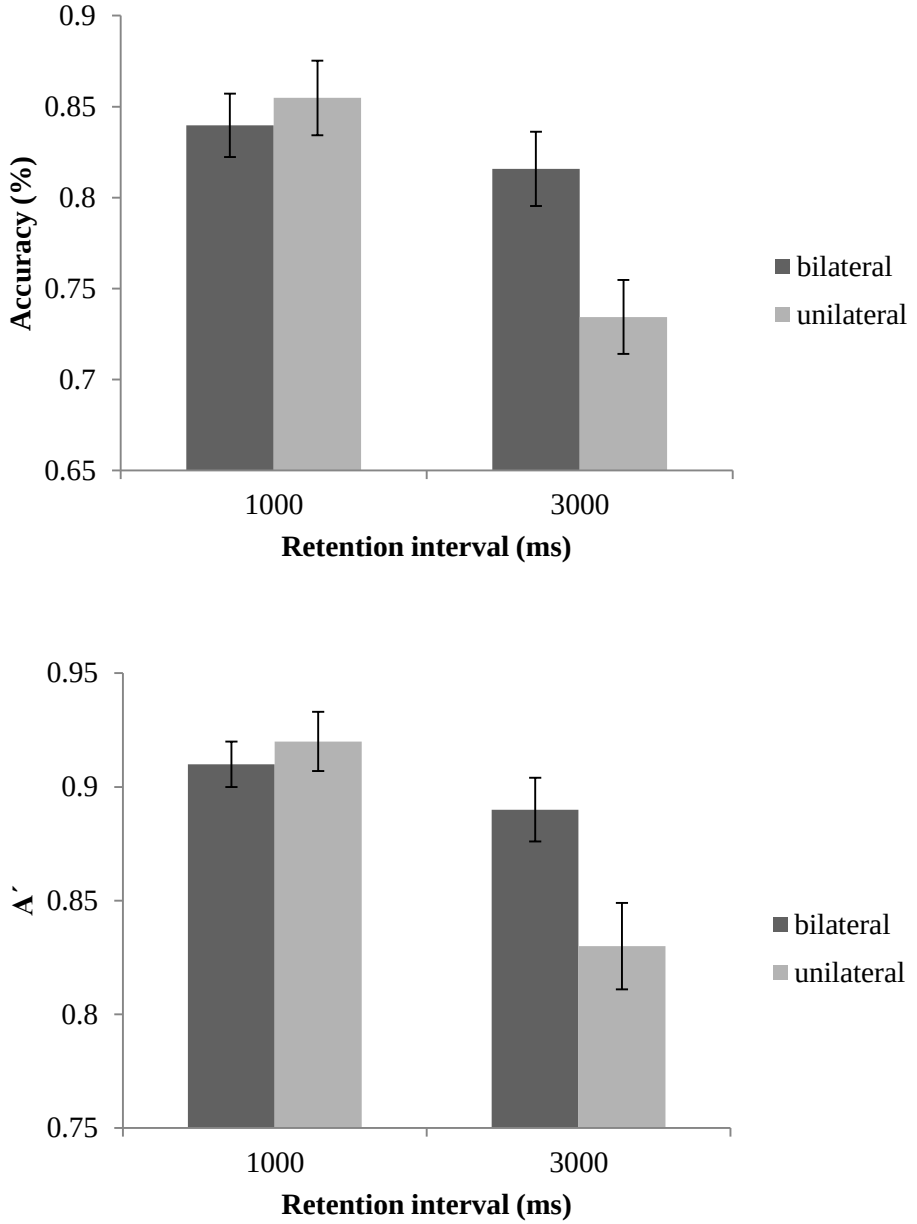

Figure 3.9: Results of Experiment 8. Response accuracy (%) and A´ as a function of retention interval (1000ms, 3000ms) and display (bilateral, unilateral). Error bars represent the standard error of the mean values.

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3.5.3 Discussion

The aim of Experiment 8 was to address whether the findings of Experiment 5 can be explained due to the attentional orienting effects of the pre-cues at encoding. Therefore, participants were required to select and process two stimuli which were

pre-cued before the array. As shown above, the results replicated the findings of Experiment 5, revealing a BFA that was influenced by the duration of the retention interval. Once again, performance in bilateral conditions remained consistent over time, whereas performance in the unilateral conditions reduced as the retention interval was increased. The findings also revealed that the pre-cues promoted the BFA only at the longest retention interval, strongly suggesting that they influenced the mnemonic component of the task.

In comparison to the findings of Experiment 6, which tested memory for the colours in the absence of the pre-cues, the findings indicate that the nature of the BFA within VSTM maintenance may depend on how an item is encoded. Specifically, the results suggest that orienting attention to item locations before presentation may allow bilateral items to better survive decay.

In removing distracters from the array and presenting only two target stimuli on each trial, with the constraint that target colours could not repeat, the requirement to remember target locations was reduced. As a result, the findings support the notion that the nature of the BFA during VSTM maintenance is not simply a feature of maintaining object locations over longer durations (Experiment 7).

3.6 General Discussion

3.6.1 Overview of the findings

The aim of Part Two was to investigate whether bilaterally encoded items can better survive decay in VSTM relative to unilaterally encoded items. As in Experiment 1, participants completed a colour change detection task which required the selection of targets from distracters on the basis of spatial pre-cues during the encoding stage (Experiment 5). In order to examine how the colours are maintained, VSTM for colour within and across hemifields was assessed over two retention intervals (1s, 3s). Replicating the results of Experiment 1, the findings revealed a BFA

suggesting that demands on selective attention at encoding can promote a BFA in colour VSTM. However, as the retention interval increased, the BFA also increased, indicating that bilateral performance remained consistent over time whereas unilateral performance declined. For that reason, the findings strongly suggest that bilateral items can better survive decay in VSTM.

Importantly, this pattern of performance was not shown to be a feature of the requirement to remember the colours or locations of the target stimuli in the absence of the selection demands at the encoding stage. In line with previous studies (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), no hemifield effects were observed for colour VSTM regardless of the manipulations to the retention interval (1s, 3s). In addition, despite confirming a BFA in location VSTM (Delvenne, 2005), the present findings revealed that the size of the BFA remained consistent over time. Therefore, the results indicate that the nature of the BFA during VSTM maintenance was influenced by the engagement of attentional selective processes at the encoding stage.

Interestingly, the effects shown in Experiment 5 were observed when the targets were simply pre-cued before the array in the absence of distracters (Experiment 8). By pre-cueing two targets at encoding, bilateral performance remained consistent over time whereas unilateral performance decreased. As a result, the findings suggest that the orienting of spatial selective attention to item locations at the encoding stage can promote the BFA within VSTM maintenance, allowing bilateral items to better survive decay.

3.6.2 Possible explanations of the findings

Previous studies suggest that spatial selective attention at the encoding stage can influence the transfer of information into the VSTM store (Botta et al., 2010; Griffin & Nobre, 2003; Makovski & Jiang, 2007; Murray et al., 2011; Schmidt et al., 2002). Those studies presented spatial pre-cues before the memory array and reported

enhanced recall of the cued items (relative to uncued items). However for the first time, the present findings suggest that directing spatial attention to stimuli locations before VSTM encoding can also influence the maintenance of the stimuli in VSTM. Consequently, the present findings provide a further understanding of the cue-related advantage in VSTM recall reported in previous studies.

The pre-cue effects on VSTM maintenance may be explained due to the fact that spatial attention, which is deployed in response to the pre-cues, also plays an important role in the subsequent rehearsal of information in memory (e.g. Awh et al., 1998; Williams et al., 2013). Indeed, research suggests that the same attentional mechanisms are deployed in perception and within memory, with evidence that the deployment of spatial attention during both stages enhances processing at the attended locations (Awh et al., 2000; Jha, 2002) and elicits activity in similar neural circuits (Corbetta et al., 2002).

With this in mind, the ability for attentional directing cues before encoding to influence the subsequent maintenance of the cued stimuli in VSTM seems plausible. However, it may be questioned how the pre-cues promote the hemifield effects observed. One possibility may be that pre-cues facilitate the deployment of spatial attention during the encoding stage to the relevant non-contiguous locations which is consequently maintained, assisting rehearsal within VSTM. Supporting this idea, Murray and colleagues (2011) demonstrated that the cue-related advantage in recall can be predicted from the neural activity elicited during the pre-cueing stage. Specifically, they showed that VSTM recall was related to electrophysiological markers associated with the initiation of anticipatory attentional shifts. The benefit of bilateral relative to unilateral pre-cues may be specifically related to the ability to divide attention more easily across hemifields relative to within hemifields (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007).

An additional explanation of the present results, which may not be mutually exclusive, concerns the effect of attentional selection on the modulation of visual processing. It is well established that a stimulus can be processed more efficiently when spatial attention is directed to its location (Posner, 1980). This effect may be expected since selective attention can enhance stimulus representations in the visual cortex (see Carrasco, 2011, for a review of those effects). In VSTM tasks, a number of studies have also revealed that the deployment of selective attention to stimuli during encoding modulates early activity in areas of the sensory cortex that code the stimuli (Gazzaley & Nobre, 2012; Rutman, Clapp, Chadwick, & Gazzaley, 2009; Zanto, Rubens, Thangavel, & Gazzaley, 2011). Importantly, those studies also demonstrated that the early modulations correlate (Rutman et al., 2009) and even causally relate (Zanto et al., 2011) to enhanced VSTM recall of the selected information.

In explaining those effects on VSTM, Rutman and colleagues (2009) suggest that the early modulation of activity may increase the fidelity of the VSTM representations which thus translates to better maintenance across the retention interval. Indeed, the present findings revealed that selection influenced the extent to which items survived decay across long retention intervals of three seconds (Experiment 5 & 8). To provide a better understanding of this effect, an examination of the neural mechanisms during the encoding and maintenance stages within a single study requires investigation. However, since VSTM maintenance activity can also be localised in visual sensory areas that code the stimuli (Harrison & Tong, 2009; Serences et al., 2009; Xing et al., 2013), one possibility may be that the early modulations promoted by selective pre-cueing influence the persistence of maintenance activity during the retention interval.

In relation to this account, the BFA may also be the result of the ability to deploy attention more effectively across hemifields to the cued locations (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007), with bilateral cues enhancing

stimuli representations to a greater extent. However, those effects may also be explained by drawing upon a functional magnetic resonance imaging (fMRI) study conducted by Scalf and Beck (2010). They showed that selective attention can indeed influence the representation of information in the visual cortex as indicated through blood oxygen level-dependent (BOLD) signal. However, they also showed that attention was less effective when multiple items were attended, as signalled by a reduction in BOLD response. Nevertheless, Scalf and Beck (2010) demonstrated that the BOLD response for multiple stimuli can be enhanced when the stimuli are divided across the two visual hemifields relative to when displayed in a single hemifield.

As a result of the retinotopic organisation of the visual cortex, Scalf and Beck (2010) suggest that that those effects may be explained due to the fact that items compete for representation to a greater extent within hemifields since they are represented by common cell populations. As a result, those competitive interactions reduce the ability for attention to enhance representations of multiple stimuli. Therefore, in relation to the present task, the BFA observed in response to selective pre-cueing (Experiment 8) may also be explained by the extent to which the selected stimuli compete for representation in the visual cortex.

3.6.3 The relationship to previous findings

The present findings compliment our previous study (Delvenne & Holt, 2012) which revealed that retro-cues can also promote a BFA in colour VSTM maintenance. Research suggests that retro-cues and pre-cues recruit a common attentional resource (Gazzaley & Nobre, 2012), however some studies suggest the presence of mechanistic differences. For instance, disparities in the behavioural effects (Makovski & Jiang, 2007) and the neural sites engaged (Tanoue, Jones, Peterson, & Berryhill, 2013) have been identified in comparisons of retro- and pre- cue effects on visual processing (for a review, see Tanoue et al., 2013). Nevertheless, Kuo and

colleagues (2012) recently confirmed the ability of retro-cues to influence VSTM maintenance by monitoring electrophysiologically the number of items maintained within VSTM on each trial. In doing so, their findings suggest that the retro-cues bias VSTM maintenance in favour of the relevant selected items. Therefore, together with the present results, the findings suggest that attentional selective processes during encoding and within VSTM maintenance can promote a BFA within VSTM maintenance.

Those findings also support the notion that the BFA observed in VSTM tasks can arise within VSTM storage and not only at the encoding stage, a contention originally proposed by Umemoto and colleagues (2010). As previously discussed, Umemoto and colleagues (2010) found that the BFA for orientation VSTM was evident when the memory stimuli were presented sequentially, thus removing the possibility that the BFA can be accounted for by encoding differences in unilateral and bilateral displays (for a discussion, see Literature Review). Furthermore, the present findings provide an extension of those effects, revealing that the BFA may also depend on the duration of the retention interval.

However, since this effect was dependent on the selection requirement during encoding (Experiment 5 & 8), the present findings suggest that the BFA within storage may also depend on how items are encoded into VSTM. Nevertheless, the findings do not rule out the possibility that the magnitude of the BFA may increase over time in the absence of those encoding requirements when longer retention intervals than three seconds are utilised. Indeed, as previously discussed, simply placing a greater demand on VSTM rehearsal may produce a BFA at longer retention intervals.

In Part One of this thesis, the effect of selection on the BFA in colour VSTM processing was confirmed. In Experiment 1, the BFA was revealed when targets were selected among distracters on the basis of spatial pre-cues before encoding.

Although further experiments indicated that filtering targets from distracters in the absence of the pre-cues (Experiment 3) still promoted the BFA, those experiments did not specifically address whether the pre-cues may also play a role in the BFA.

Experiment 8 provides a better understanding of this encoding manipulation indicating that spatial pre-cues can also promote a BFA in VSTM. The findings suggest that the BFA was dependent on the mnemonic component of the task since the BFA only emerged when the retention interval was increased (3s). As previously discussed, at the shorter retention intervals (1s), the pre-cues failed to promote the BFA.

In line with this finding, previous non-mnemonic studies (Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009) failed to show a BFA when targets were simply pre-cued in the absence of distracters, supporting that the emergence of the BFA relies on the mnemonic component of the task (Experiment 8). Instead, the BFA in those studies depended on the requirement to filter targets from distracters, suggesting that the BFA in encoding limited tasks is a feature of attentional filtering.

Therefore, attentional filtering and attentional orienting may have dissociable effects on the observance of the BFA in VSTM. Specifically, the present findings raise the possibility that those encoding manipulations may result in the emergence of the BFA at different stages in VSTM processing. Whereas filtering can promote a BFA during the encoding stage (e.g. Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009), pre-cues may exclusively lead to the emergence of a BFA within the mnemonic component of a task, at least when processing two target stimuli.

3.6.4 Conclusion

In sum, the present findings support the findings of Part One, highlighting that attentional selective processes can promote a BFA in colour VSTM. In addition, the

findings suggest that selective attention at encoding can also influence the maintenance of information in memory, allowing bilateral items to be more resistant to decay. Together with Part One, the findings also provide a further understanding of the selection manipulation utilised in previous experiments, suggesting that both attentional filtering and the orienting of spatial attention can promote the BFA in VSTM tasks.

4 General discussion

4.1 Thesis aims and synthesis of the findings

The purpose of the present thesis was to examine how VSTM processing is influenced by the spatial distribution of information across the visual field. Specifically, the thesis aimed to determine the conditions in which a BFA can be observed within VSTM. Until recently, the BFA has been investigated in mainly perceptually limited tasks (e.g. Alvarez & Cavanagh, 2005) and thus it remains to be fully understood how this translates to mnemonic processing.

A limited number of experiments provided some preliminary understanding of the BFA in VSTM (Delvenne, 2005; Delvenne et al., 2011b; Umemoto et al., 2010). They revealed that the BFA is likely to be limited by the type of stimuli that are stored. Whereas Delvenne (2005) and Umemoto and colleagues (2010) observed a BFA when participants were required to remember spatial locations and orientations respectively, no BFA was revealed when participants were required to memorise colours (Delvenne, 2005; Delvenne et al., 2011b). Considering the dissociation between spatial and identity processing in the brain (Ungerleider & Mishkin, 1982) which has also been shown to extend to VSTM processing (e.g. Darling et al., 2009; Ventre-Dominey et al., 2005), a stimulus domain hypothesis, which posits that the BFA may only be a feature of spatial processing, was identified as a plausible explanation of the BFA (Alvarez & Cavanagh, 2005; Delvenne, 2005).

However, since then, a number of non-mnemonic studies have provided evidence against this stimulus domain hypothesis (Alvarez et al., 2012; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009; Reardon et al., 2009), since those studies revealed a BFA in identity processing tasks. Instead, the studies showed that the

observance of the BFA relied on the task demands on attentional selective processing. Specifically, each study demonstrated that the BFA depended on the requirement to select and process target stimuli amidst simultaneously displayed distracter stimuli. Indeed, Alvarez and Cavanagh (2005) also hypothesised that the BFA may be a signature of spatial selective attention due to the possibility of independent attentional resources within each cerebral hemisphere as indicated in their experiment.

In response to those findings, the present thesis investigated whether the BFA in VSTM is also constrained by the demands on attentional selection. Due to the failure to reveal a BFA in colour VSTM (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), the role of selection was addressed in colour change detection tasks. It was hypothesised that if the BFA is mainly limited by the type of stimuli to be processed, then no BFA should emerge, however if the BFA is constrained by attentional selective processes, then a BFA for colour may be expected when the task demands on selection are increased.

The experiments of Part One confirmed the role of selection in the BFA in VSTM, revealing the emergence of a BFA in colour VSTM when participants were required to select and subsequently remember the colours of target stimuli presented amidst distracter stimuli at the encoding stage. Drawing upon previous non-mnemonic studies which have revealed a BFA, those effects may be explained due to the disruptive effects of attentional suppressive surrounds within hemifields (Chakravarthi & Cavanagh, 2009), and the better ability to divide attention to non-contiguous locations (Awh & Pashler, 2000; Kraft et al., 2005; Malinowski et al., 2007) and segregate spatially distributed information (Reardon et al., 2009) across hemifields. Indeed, the ability of each hemisphere to independently allocate attentional resources in parallel (Alvarez & Cavanagh, 2005) may also be fundamental to those effects.

Considering the previous demonstrations of a BFA in non-mnemonic selection tasks (e.g. Chakravarthi & Cavanagh, 2009), it is plausible that task demands on selection may promote a BFA at the stage of VSTM encoding. However, given that the same attentional mechanisms have been shown to operate beyond the encoding stage, with evidence that spatial selective attention also acts as a rehearsal mechanism within VSTM (Awh et al., 1998; Williams et al., 2013), it was hypothesised that bilateral items may also better survive decay in VSTM.

Therefore, in Part Two, the BFA was examined in similar colour change detection tasks, however the retention interval was manipulated (1s, 3s). Supporting a role of attentional selection within memory, the findings revealed that the BFA increased as the retention interval increased. Specifically, the results revealed that bilateral items better survived decay in VSTM relative to unilateral items.

However, those results were dependent on the task demands on spatial based selection at the encoding stage. Without the requirement to select the memory stimuli on the basis of pre-cues before the array, bilateral items decayed in the same way as unilateral items. As a result, the findings strongly suggest that how items are encoded into VSTM can influence how they are subsequently maintained. Specifically, the findings suggest that bilateral maintenance can be facilitated by the orienting of spatial attention to object locations before presentation.

Overall, the findings of this thesis strongly support a role of attentional selection in the BFA within VSTM. On closer inspection, the findings identify two attentional processes that can promote the BFA; the filtering of targets from distracters (Part One) and the orienting of spatial attention to object locations (Part Two). Whereas previous studies suggest that attentional filtering may produce a BFA at the encoding stage of VSTM tasks (e.g. Chakravarthi & Cavanagh, 2009; Reardon et al., 2009), the orienting of spatial attention at encoding was exclusively shown to promote a BFA within VSTM maintenance (Experiment 8).

In line with previous suggestions that the BFA is specifically a feature of spatial attention (Alvarez & Cavanagh, 2005; Alvarez et al., 2012), the selection demands in each of the experiments reported here predominately required spatial selective processes. Although the BFA was revealed in a feature based selection task (Experiment 3), it is evident that the task was also dominated by spatial based selection, since targets and distracters were presented in distinct locations (for a discussion, see Part One). Supporting the BFA as a signature of spatial selective attention, recent research has shown that spatial selection can coordinate neural firing independently within each hemisphere (Cohen & Maunsell, 2011). On the other hand, the same study revealed that feature based selection coordinates neural firing across the whole visual field, and is therefore unlikely to produce hemifield effects in visual processing.

4.2 Explanations of the BFA in previous VSTM tasks

4.2.1 The BFA in spatial VSTM

As outlined above, previous studies have reported a BFA in tasks which require VSTM for spatial locations (Delvenne, 2005) and orientations (Umemoto et al., 2010). As previously discussed, both studies may be dominated by spatial VSTM processing, since memory for the spatial characteristics of the stimuli can be expected to facilitate performance in both tasks (see literature review for a further discussion). However, since those studies did not require participants to select targets from distracters, nor were spatial pre-cues presented before the array, it may be questioned how the process of attentional selection can explain those findings.

Although the task demands on selective attention were not explicitly manipulated in those studies, the BFA observed may still be explained by the engagement of spatial selective attention since research has emphasised a highly extrinsic

relationship between spatial selective attention and spatial memory processing (for reviews, see Awh & Jonides, 2001; Awh, Vogel, & Oh, 2006; Theeuwes, Belopolsky, & Olivers, 2009). For instance, in a review of evidence, Awh and Jonides (2001) highlighted the existence of a strong functional relationship between spatial short-term memory and spatial selective attention, with evidence that spatial selective attention is crucial to spatial short-term memory maintenance (e.g. Awh et al., 1998). Indeed, as previously discussed, disrupting the deployment of spatial attention to the to-be-remembered locations during the retention interval, has been shown to reduce spatial memory performance (Awh et al., 1998).

Furthermore, Awh and Jonides (2001) highlighted that both spatial short-term memory and spatial selective attention rely on the same neural network of frontal and parietal sites. In addition, electrophysiological studies have also demonstrated that maintaining a location in spatial short-term memory and simply attending to a location in perception, elicit highly similar neural activity in early areas of the visual cortex (Awh et al., 2000; Jha, 2002). Therefore, it is evident that both a neuroanatomical and functional relationship can be identified between spatial memory and spatial selective attention.

Although spatial VSTM processing exhibits a BFA, the findings of the present thesis as well as previous research (Alvarez et al., 2012), suggest that this spatial memory component may not be crucial to the observance of the BFA across all VSTM tasks. In Experiment 8, despite presenting only two memory stimuli in the absence of distracters, with the constraint that the to-be-remembered colours could not repeat (thus rendering the maintenance of object locations redundant), the BFA was still observed within VSTM storage. In addition, Alvarez and colleagues (2012; Experiment 3A) demonstrated that tasks which require sustained spatial selection across intervals of one second can promote a BFA in the absence of spatial working memory load. Therefore, collectively, those results suggest that the BFA in

VSTM is primarily reliant on the engagement of spatial selective processes, whether or not VSTM for spatial information is necessary for the task.

4.2.2 The absence of the BFA in colour VSTM

As previously discussed, although the BFA has been demonstrated in spatial VSTM processing tasks (Delvenne, 2005; Umemoto et al., 2010), a number of studies (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012), including the findings of the present thesis, have consistently failed to reveal a BFA in colour change detection tasks. In relation to the present findings, one possibility is that the failure to observe a BFA in those tasks can be explained by the extent to which the task engages spatial selective processing.

Indeed, the present experiments suggest that the task demands on spatial selective processing need to be increased in order to observe a BFA in colour VSTM (Experiments 1, 3, 5 & 8). Supporting this contention, previous research has failed to identify a role of spatial selective attention in the rehearsal of identity information in VSTM (Awh et al., 1998). Although Awh and colleagues (1998) revealed clear evidence that spatial attention was deployed to the to-be-remembered spatial locations in their spatial memory task, the same study failed to show that spatial attention was maintained to stimuli locations when rehearsing identities.

However, recently, research has shown that spatial selective attention may to some extent play a role in the rehearsal of identity information (Williams et al., 2013). Specifically, Williams and colleagues (2013) revealed that preventing shifts of spatial attention to the locations of the memory stimuli during rehearsal subsequently reduced memory for the colours of the stimuli. However, those effects were constrained by the number of memory stimuli in the task. Therefore, it may be the case that colour VSTM processing relies to a lesser extent on spatial selective attention relative to spatial VSTM processing, and as a result, does not exhibit a BFA when the task demands on selection are low.

Supporting this possibility, Williams and colleagues (2013) also highlight that colour VSTM may rely on different mechanisms relative to spatial VSTM to support rehearsal. Whereas their study revealed that eye-movements to the locations of the to-be-remembered colours facilitated memory performance, the same effect has not been replicated in a recent spatial location VSTM task (Godijn & Theeuwes, 2013). For that reason, Williams and colleagues (2013) suggest that those differences may be another signature of the dissociation between spatial and identity processing previously reported (Ungerleider & Mishkin, 1982).

Therefore, the BFA for spatial information (Delvenne, 2005; Umemoto et al., 2010) but not for colours (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012) observed in previous VSTM change detection tasks, may be explained due to the reliance that those stimulus domains place on spatial selective attention to support VSTM processing. Although spatial memory rehearsal has been examined in many studies (for a review, see Awh & Jonides, 2001), the mechanisms underlying the rehearsal of colour in VSTM has been subject to considerably less research. A further examination of the rehearsal mechanisms supporting each of those stimulus domains may provide a further understanding of the conditions which promote a BFA in VSTM.

4.3 Implications of the findings

4.3.1 A further understanding of the BFA

As described in the literature review, the BFA in visual processing has been investigated in many non-mnemonic perceptual processing tasks (e.g. Alvarez & Cavanagh, 2005; Belger & Banich, 1992, 1998; Reardon et al., 2009). However, the observance of a BFA within VSTM processing has been examined to a much lesser extent. To date, only one study has explicitly tested whether the BFA can occur beyond perceptual processing and within VSTM storage (Umemoto et al., 2010).

Umemoto and colleagues (2010) investigated this by equating the encoding conditions across bilateral and unilateral displays, which removed the possibility that differences at the encoding stage can promote the BFA. By presenting the stimuli sequentially, one hemifield at a time, they observed that the BFA still emerged, highlighting that the BFA can also arise within VSTM storage. By directly manipulating the retention interval of the VSTM processing task, Part Two provides confirmatory evidence that the BFA is also a feature of mnemonic processing. In addition, the present findings suggest that the BFA within storage also extends to the maintenance of identity information in VSTM.

A dominant view in the BFA literature provided by Banich and colleagues (e.g. Banich & Belger, 1990; Belger & Banich, 1992, 1998; Weissman & Banich, 2000), asserts that the BFA in visual processing tasks arises due to the complexity of the task, with only complex tasks exhibiting a BFA. As previously discussed, their hypothesis suggests that in order to observe a BFA, tasks must be sufficiently complex so that the costs of hemispheric integration are outweighed by the benefit of extra computational power. The complexity of the task may be enhanced by increasing the number of processing steps (e.g. Banich & Belger, 1990) or by increasing the number of stimuli to be processed (Belger & Banich, 1992, 1998; Merola & Liederman, 1990).

However, the findings of the present thesis suggest that task complexity is unlikely to account for the BFA observed. For instance, although performance in the no distracter conditions of Experiment 1 indicated a significantly greater level of task difficulty relative to the distracter conditions, the BFA was not observed. Instead, the observance of the BFA relied on the task demands on selection at encoding. Furthermore, despite assessing colour VSTM processing across a range of set sizes, from two to six items (see Appendix), the present experiments revealed no evidence of a BFA in colour processing as the number of stimuli increased. Therefore, the present thesis suggests that the BFA may specifically arise due to

the demands on selective attention, rather than being solely due to a general task complexity manipulation. Indeed, similar findings were reported by Alvarez and colleagues (2012; Experiment 4) indicating that the level of task difficulty across their selection based tasks failed to predict the observance of the BFA in those tasks.

4.3.2 The relationship between VSTM and spatial attention

As highlighted throughout this thesis, a strong relationship has been documented between visual spatial attention and VSTM processing (for reviews, see Awh & Jonides, 2001; Chun, 2011; Kiyonaga & Egner, 2013; Olivers, 2008). Not only have studies shown that both processes share a similar capacity limit (Cavanagh & Alvarez, 2005; Luck & Vogel, 1997; Oksama & Hyönä, 2004; Pylyshyn & Storm, 1988; Vogel et al., 2001) and neural circuitry (Awh & Jonides, 2001), research has shown that attention plays a functional role at all stages of VSTM processing including encoding (Schmidt et al., 2002), maintenance (Awh et al., 1998) and retrieval (Theeuwes, Kramer, & Irwin, 2011).

The present findings provide a further understanding of this functional relationship. Namely, the results of Experiment 8 provide important extensions to the view that spatial selection at the encoding stage can promote the transfer of items into VSTM (Botta et al., 2010; Griffin & Nobre, 2003; Makovski & Jiang, 2007; Murray et al., 2011; Schmidt et al., 2002). The observance of the BFA in Experiment 8, which was dependent on the presence of pre-cues, indicates that the effectiveness of selective attention on VSTM transfer is constrained by the distribution of the stimuli within and across hemifields. Most importantly however, the findings indicate that selection at encoding not only promotes the transfer of items into VSTM (Schmidt et al., 2002), but can also support the maintenance of information within VSTM (Experiments 5 & 8).

Previous research suggests that both endogenous and exogenous attention can influence the transfer of information into VSTM (Botta et al., 2010; Schmidt et al., 2002). Whereas endogenous attention is characterised as a voluntary form of attention that is deployed in a top-down manner and sustained in nature, exogenous attention is considered to be an automatic form of attention that is highly transient and related to bottom-up processing (for a discussion, see Carrasco, 2011).

To engage those types of attention, different experimental paradigms are utilised (see Botta et al., 2010, for an illustration). Exogenous attention is oriented with the use of spatial cues in the periphery, as shown in the present experiments (Experiments 1, 2, 5 & 8). In contrast, endogenous attention is typically oriented using a symbolic cue in the centre of the screen which signifies the relevant spatial location to be attended. Due to the temporal differences between exogenous and endogenous attention, with exogenous attention dissipating beyond 100-120ms and endogenous requiring at least 300ms to be deployed successfully (Carrasco, 2011), the duration of the cue and the cue-to-target delays are manipulated accordingly (see Botta et al., 2010).

Given the dichotomy between exogenous and endogenous spatial attention, it may be questioned which attentional mechanism is responsible for the BFA in the present selection based experiments. Although it appears to involve exogenous attentional orienting, since the BFA was observed in response to spatial peripheral cues (Experiment 8), the results of Experiment 1 suggest this is unlikely to be the case. The results revealed that the BFA only emerged when the cue-to-target delay was increased from 50ms to 500ms. Therefore, due to the differing temporal characteristics of exogenous and endogenous attention discussed above, it is likely that the BFA in VSTM is actually contingent on endogenous spatial attention.

As previously discussed, state based models of memory offer a further explanation of how attention influences memory processing. Specifically, those models suggest that attention alters the representational state of items in memory, highlighting that relevant items in memory are maintained in an active state when encompassed within the focus of attention (Cowan, 1995; McElree, 1996; Oberauer, 2002). As a result, the state based models indicate a strong relationship between attention and short-term retention, and therefore may support the plausibility of an attentional mechanism promoting the BFA in memory processing.

However, the state based models of memory diverge in their explanations of how the focus of attention is deployed. Whereas Cowan's (1995) model suggests that the focus of attention can be distributed to multiple items, modifications of this model have incorporated a narrower, single focus of attention that is deployed to individual items in a switching manner (McElree, 1996; Oberauer, 2002). As a result, it may be questioned which mechanism can explain the presence of the BFA in this thesis.

As discussed below, the role of a multi-focal attentional mechanism in the BFA has gained more support relative to a single attentional focus, due to limits in the time course of attentional switching within and across hemifields (Chakravathi & VanRullen, 2011). Although support for a single focus of attention in memory was highlighted in previous retro-cue studies which demonstrated that only a single retro-cue could be effectively utilised (e.g. Makovski & Jiang, 2007), we recently showed that two retro-cues can improve memory when divided between the two visual hemifields (Delvenne & Holt 2012). Those findings support the possibility that attention can be divided within memory and promote a BFA. Furthermore, while research suggests that the single focus may encompass multiple items once chunked together (Oberauer & Hein, 2012), studies indicate that this mechanism is also unlikely to promote a BFA since perceptual grouping and integration processes

have been shown to be superior within a hemifield relative to across hemifields (Butcher & Cavanagh, 2008; Pillow & Rubin, 2002).

Nevertheless, with a better ability to split attention to non-contiguous locations across hemifields (Delvenne & Holt, 2012), one possibility is that the BFA reflects the existence of a single focus of attention within each hemifield. The presence of two attentional foci, which enable attention to be divided across hemifields but not within a single hemifield, may offer a plausible explanation for the BFA observed in tasks which are dominated by attentional selection (e.g. Experiment 1). In addition, this hypothesis may reconcile the opposing single versus multi-focal accounts of attention incorporated in previous models of memory (Cowan, 1995; McElree, 1996; Oberauer, 2002), highlighting that both mechanisms exist but are constrained by hemifield alignment. An assessment of the attentional landscape within and across hemifields may enable this hypothesis to be directly assessed.

4.3.3 The existence of multi-focal spatial attention

The role of selective attention in the BFA suggests that attentional deployment is more efficient across hemifields relative to within a single hemifield. Non-mnemonic studies which have supported a role of spatial selective attention in the BFA (Alvarez & Cavanagh, 2005; Alvarez et al., 2012; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009), suggest that those effects are likely to be attributed to a multi-focal attentional mechanism. Indeed, both behavioural (Awh & Pashler, 2000; Kraft et al., 2005) and electrophysiological studies (Malinowski et al., 2007) have suggested that spatial attention can be divided more easily across hemifields.

Nevertheless, in a review of those studies, Jans and colleagues (2010) concluded that the existence of multi-focal attention cannot yet be firmly accepted. As a result, they suggest that a number of methodological criteria must be satisfied in order to provide clear evidence of a multi-focal attentional mechanism. According to Jans

and colleagues (2010), experimental tasks need to be attentionally demanding, with short stimulus presentation times (to remove the possibility of attentional shifts, 100ms or less), and utilise cue-to-target delays that facilitate the allocation of endogenous attention (500ms or more).

To some extent, the nature of the present experiments which observed a BFA fulfilled those criteria and therefore may support a role of multi-focal attention in the BFA. For instance, the BFA was observed when the task demands on spatial based attention were increased, when cue-to-target delays were extended to 500ms (see Experiment 1), and when memory array presentation times were relatively short (100ms or 150ms). In addition, although recent evidence suggests that a unitary focus of endogenous attention may be switched more rapidly in bilateral relative to unilateral displays (Chakravarthi & VanRullen, 2011), this attentional mechanism is unlikely to explain the BFA in the present experiments. Given that endogenous attentional shifts were estimated to take at least 250ms (Chakravarthi & VanRullen, 2011), the requirement to process multiple stimuli within 150ms in the present experiments renders this mechanism unlikely.

However, Jans and colleagues (2010) also highlight that an assessment of the allocation of spatial attention across the visual field should be examined in order to determine whether the attentional focus has been divided. Although the present experiments did not address this, the results of Experiment 5, which outline the influence of distracter stimuli positions on the selection and memory for target stimuli, may to some extent support the role of non-contiguous attentional distributions. The findings revealed that distracters near to the target interfered to a greater extent with target processing relative to distracters that were further away, suggesting the possibility of non-contiguous attentional distributions with maximal enhancement near to the cued locations. However, this distracter position effect did not interact with the observance of the BFA. Therefore, although the present experiments may to some extent support the existence of multifocal attention, a

further examination of the attentional landscape around target locations is required to arrive at firm conclusions.

4.3.4 The capacities of VSTM and spatial attention

Alvarez and Cavanagh's (2005) striking demonstration of the BFA in attentional tracking strongly suggests that attentional processing capacity is independent within each cerebral hemisphere since participants could track twice as many stimuli when the stimuli were displayed across hemifields. As a result, the findings highlight that previous estimates of a four-item attentional capacity (Cavanagh & Alvarez, 2005; Oksama & Hyönä, 2004; Pylyshyn & Storm, 1988) may be better conceptualised as a capacity limit of two objects within each hemisphere.

Likewise, research suggests that VSTM also has a capacity limit of 3-4 objects (Luck & Vogel, 1997; Vogel et al., 2001). However, the absence of the BFA in colour VSTM shown consistently in previous studies (Delvenne, 2005; Delvenne et al., 2011b; Mance et al., 2012) when spatial selection demands are not explicitly increased (see Part One), suggests that the cerebral hemispheres share a single capacity-limited VSTM resource. Indeed, Delvenne and colleagues' (2011b) electrophysiological study revealed that contralateral delay activity (CDA, see Vogel & Machizawa, 2004) measured separately in each hemisphere indicated the total number of items held in VSTM regardless of their position in the visual field. If each hemisphere has its own VSTM processing capacity then it can be expected that the CDA should be modulated by the number of items remembered in the contralateral hemifield only.

Yet, since the BFA has been observed in VSTM tasks which have a distinct spatial processing requirement, such as the tasks which were dominated by spatial selection in the present thesis (e.g. Experiment 1), it can be identified that the number of items held in VSTM can be constrained by the capacity limits of attentional processing. However, although spatial VSTM may exhibit a BFA (e.g.

Delvenne, 2005; Umemoto et al., 2010), the pattern of performance in spatial memory tasks has been inconsistent with the existence of totally independent attentional resources within each hemisphere (Delvenne, 2005).

Therefore, it may be the case that complete hemispheric independence in attentional processing does not readily translate to VSTM since VSTM processing is likely to rely on a single resource (Delvenne et al., 2011b). However, on the other hand, the findings may also question the existence of complete hemispheric independence in attentional processing. Indeed, recently, Hudson and colleagues (2012) failed to replicate Alvarez and Cavanagh's (2005) results, despite utilising the same task whilst increasing statistical power. Instead, they found that attentional tracking produced only a BFA in performance and therefore suggest that the notion of *partially* independent attentional resources within each hemisphere may better explain attentional processing capacity within and across hemifields (Hudson et al., 2012).

Nevertheless, since the hemifield alignment of visual stimuli may influence the number of items held in VSTM when spatial attention is engaged, obtaining accurate estimates of VSTM capacity may benefit from an assessment which manipulates the spatial distribution of information within and across hemifields. This may be particularly useful when assessing VSTM in older adult populations. For instance, research suggests that in order to deal with age-related neural decline, older adults rely on bihemispheric processing to a greater extent than younger adults (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz et al., 2000). Consistent with this finding, the observance of the BFA has been shown to be contingent on age, with a number of tasks revealing a BFA only in older adults (Guzzetti & Daini, 2014; Reuter-Lorenz & Stanczak, 2000; Reuter-Lorenz et al., 1999). As a result, those studies suggest that VSTM performance in unilateral arrays may highly underestimate VSTM capacity in older adults.

4.4 Conclusions

The present thesis provides a novel understanding of VSTM capacity and the way it is influenced by the spatial distribution of information in the visual field. Specifically, the thesis identifies and tests two hypotheses that have been proposed in the literature, and in doing so, provides an understanding of the conditions in which a BFA may arise within VSTM processing. As a result, the findings also offer a plausible explanation for the absence of a BFA in colour VSTM processing tasks despite demonstrations of the BFA in other stimulus domains (e.g. Delvenne, 2005). At a greater level, the research provides a further step in the comprehension of how the brain's information processing capacities are distributed between the two cerebral hemispheres. These findings not only have important consequences for our understanding of VSTM, but also attention and interhemispheric communication more generally.

To confirm the generality of the present findings, a further step will be to discover whether the results can be replicated across different set sizes and experimental paradigms. At present, the findings are confined to the change detection paradigm and to the selection of only two single-featured stimuli. Replication across a variety of set sizes and other recall procedures (e.g. Umemoto et al., 2010) may uncover whether there are limits to the BFA in VSTM. Electrophysiological investigations, which measure online the number of items maintained in VSTM (e.g. Delvenne et al., 2011b), will be highly advantageous in future research. Delvenne and colleagues' (2011b) electrophysiological paradigm, which recorded the CDA (Vogel & Machizawa, 2004) to provide a measure of VSTM capacity, may be utilised to inform further investigations.

In the present thesis, two stages of VSTM processing, encoding and maintenance, have been examined to understand the conditions in which the BFA may emerge. To provide a further understanding of the BFA in VSTM, research may investigate

whether other stages of VSTM processing are also subject to hemifield effects. For instance, an avenue for further research may address whether VSTM consolidation, the intermediate process between VSTM encoding and maintenance (see Vogel, Woodman, & Luck, 2006), is also influenced by the allocation of selective attention. Investigating differences within and across hemifields at distinct stages of VSTM processing will not only afford a deeper understanding of the conditions in which a BFA may emerge, but may also provide a better understanding of the highly limited capacity system of VSTM.

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6 Appendix

Preliminary research: Confirming the absence of a BFA in colour VSTM.

6.1 Overview

In the experiments below the absence of a BFA in colour VSTM was confirmed. In Experiment 1, the number of colours to remember (2, 4, 6) and the type of stimulus presentation (sequential, simultaneous) was manipulated. In Experiment 2, a single probe rather than a whole probe display was utilised in the test array.

6.2 Experiment 1

6.2.1 Method

6.2.1.1 Participants

Twenty-five subjects completed the experiment (20 females; mean age = 19.56 years; range = 18 - 28 years). All participants had normal or corrected-to-normal visual acuity and correct colour vision, as indicated through self-report.

6.2.1.2 Stimuli and procedure

The stimuli were displayed on a grey screen background (127 of red, blue, and green phosphors) which was divided into four invisible quadrants. At a viewing distance of approximately 60cm, each quadrant subtended approximately 3.79° x 3.79° and was positioned so that the centre of each quadrant was 3.16° from the horizontal and vertical meridian.

On each trial, a white fixation point was presented in the centre of the display (500ms) followed by a memory array consisting of two, four or six coloured squares

(each subtending .63° x .63°). One of eight discriminative colours (red, blue, pink, green, yellow, turquoise, black and white) was randomly allocated to each stimulus. In order to evoke articulatory suppression, participants verbally rehearsed a series of three digits at a rate of three digits per second.

The squares were distributed equally across two horizontal quadrants (bilateral presentation) or two vertical quadrants (unilateral presentation). A minimum distance of 1.42° separated the squares (centre-centre). The repetition of colour was not possible within a quadrant but could occur across quadrants. In addition, the squares were presented either simultaneously for 150ms (simultaneous presentation), or the relevant quadrants were presented sequentially, each for 150ms with an inter-trial interval of 500ms.

After the presentation of the memory array, a blank retention interval (1000ms) was displayed followed by a test array. The stimuli were presented simultaneously in the test array. In 50% of the trials, one square changed colour relative to its appearance in the memory array. The new colour was chosen from a remaining colour that was not used within the same quadrant, however colour repetition across quadrants was possible. Participants were required to indicate as accurately as possible whether any of the squares had changed colour by selecting the relevant key (1= no change, 2= change).

Therefore, the experiment consisted of twelve possible conditions. There were three set sizes (size 2, size 4, size 6), two types of presentation (simultaneous, sequential) and two types of display (bilateral, unilateral). Each condition had 32 trials resulting in a total of 384 trials which were tested in eight equal blocks. The presentation conditions were blocked separately, with 50% of subjects completing four blocks of the sequential presentation conditions first, followed by four blocks of the simultaneous presentation condition. Within each block, the remaining

conditions were presented randomly. Participants completed 10 practice trials before each presentation condition.

6.2.2 Results

Mean response accuracy was analysed in a three-way 2 (presentation: sequential, simultaneous) x 3 (set size: 2, 4, 6) x 2 (display: bilateral, unilateral) repeated measures ANOVA. The results revealed an effect of size [$F(2, 48) = 326.67$, $p < .001$, $\eta_p^2 = .93$], indicating a decrease in accuracy with an increase in set size. This was confirmed with Bonferroni pairwise comparisons which showed better performance at size 2 relative to size 4 ($p < .001$) and size 6 ($p < .001$) and better performance at size 4 relative to size 6 ($p < .001$). However, no other main effects or interactions were revealed ($p > .12$; see Table 1).

The possibility of visual field asymmetries in performance were also examined by comparing performance in the left and right unilateral trials, and the upper and lower bilateral trials. However paired sample t-tests failed to reveal any significant differences ($p > .80$).

The same analysis on A-Prime[2] (A´) from signal detection theory (Aaronson & Watts, 1987; Grier, 1971; Pollack & Norman, 1964) and Cowan's K[3] (Cowan, 2001), replicated the results above. However, those analyses revealed a tendency for better performance in the simultaneous relative to the sequential presentation conditions [A´: $F (1, 24) = 4.68$, $p<. 05$, $\eta_p^2 = .16$] [K: $F (1, 24) = 3.37$, $p = .079$, $\eta_p^2 = .12$].

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[2] $A' = 0.5 + (x - y)(1 + x - y) / 4x(1 - y)$
where x is the probability of a hit and y is the probability of a false alarm

[3] $K = s(x - y)$
where s is the total set size, x is the probability of a hit and y is the probability of a false alarm

Table 1: Mean response accuracy (%) across all conditions. The standard error is denoted in each bracket.

	Presentation x Display			
	Simultaneous		Sequential	
Size	Bilateral	Unilateral	Bilateral	Unilateral
2	0.92 (.01)	0.92 (.01)	0.92 (.01)	0.92 (.01)
4	0.79 (.02)	0.77 (.02)	0.78 (.02)	0.74 (.02)
6	0.69 (.01)	0.68 (.02)	0.67 (.02)	0.65 (.02)

6.3 Experiment 2

6.3.1 Method

6.3.1.1 Participants

Eleven subjects completed the experiment (9 females; mean age = 19.18 years; range = 18 - 21 years). All participants had normal or corrected-to-normal visual acuity and correct colour vision, as indicated through self-report.

6.3.1.2 Stimuli and procedure

As in Experiment 1, the grey screen background was divided into four invisible quadrants subtending 4.58° x 4.58° which were positioned 3.74° from the horizontal and vertical meridian. On each trial, a white fixation point was presented in the centre of the display (500ms) followed by a memory array consisting of four simultaneously displayed coloured squares (each subtending .76° x .76°) for 150ms. The colour of each square was randomly selected from six discriminable colours (blue, green, pink, red, turquoise, and yellow) with the constraint that a

single colour could not repeat within a given display. In order to evoke articulatory suppression, participants verbally rehearsed a series of three digits throughout each trial. In 50% of the trials, the squares were distributed equally across two horizontal quadrants (bilateral presentation), whereas in the remaining trials the stimuli were distributed equally across two vertical quadrants (unilateral presentation). A minimum distance of 1.6° separated the squares (centre-centre).

After a retention interval of 1000ms, participants were presented with a single coloured square in the centre of the screen. The colour either matched one of the previous colours in the memory array (50% of trials) or was a new colour. Participants were required to indicate as accurately as possible whether the colour was the same or different relative to the colours in the memory array. The response was made by selecting the relevant key on the keyboard (1= no change, 2= change). In total, participants completed 96 trials which were randomly distributed into two blocks of 48 trials. In addition, participants completed 10 practice trials.

6.3.2 Results

Mean response accuracy between unilateral and bilateral conditions was compared with a paired sample t-test. The results revealed no difference between bilateral and unilateral displays ($p > .20$; see Table 2). Furthermore, paired sample t-tests showed no difference between left and right unilateral trials, or between upper and lower bilateral trials ($p > .11$), suggesting no visual field asymmetries in performance. The analysis on A´ and K replicated those findings with the exception that the A´ analysis revealed that performance in the left visual field was greater than performance in the right visual field [$t(10)= 2.37$, $p< .05$, $d = .76$].

Table 2: Mean response accuracy (%) for bilateral and unilateral displays. The standard error is denoted in each bracket.

Display	
Bilateral	Unilateral
.80 (.03)	.77 (.03)